Department of Geodetic Science and Surveying

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PREFACE

These projects are under the supervision of Professor Ivan I. Mueller, Department of Geodetic Science and Surveying, The Ohio State University. The Science Advisor of RF 711055 is Dr. David E. Smith, Code 921, Geodynamics Branch, and the Technical Officer is Mr. Jean Welker, Code 903, Technology Applications Center. The Technical Officer for RF 712407 is Mr. C. Stephanides, Code 942. The latter three are at NASA/GSFC, Greenbelt, Maryland 20771.

TABLE OF CONTENTS

1. TECHNICAL OBJECTIVES

1. Optimal Utilization of Laser and VLBI Observations for Reference Frames for Geodynamics (Grant NSG 5265)
2. Optimal Utilization of Satellite-Borne Laser Ranging System (Grant NSG 5265) Completed.
3. Geodetic Utilization of NAVSTAR Geodetic Positioning System (Grant NSG 5265) Completed.
4. Utilization of Range Difference Observations in Geodynamics (Contract NAS 5-25888)

2. ACTIVITIES

2.1 Investigations Related to the Establishment and Maintenance of a Conventional Terrestrial Reference System

2.11 Introduction

> There seems to be general agreement that the new CTS frame conceptually be defined similarly to the CIO-BIH system, i.e., it should be attached to observatories located on the surface of the earth. The main difference in concept is that these can no longer be assumed motionless with respect to each other. Also they must be equipped with advanced goedetic instrumentation like VLBI or lasers, which are no longer referenced to the local plumblines.
>
> [Mueller, 1981a]

In other words, with the advent of new techniques (hence, the substantial increase of accuracy), the earth can no longer be thought of as rigid. This is particularly apparent considering the stated requirement of one-day earth rotation and two-day polar motion averages to 5 cm accuracy [Mueller, 1981b].

The following sections summarize the progress of investigations on the definition and maintenance of a CTS by a global network of VLBI and laser stations which can be thought of as defining the

vertices of a polyhedron [Van Gelder, 1978]. The function of the CTS can be divided into two aspects. The first is to monitor the external (or global) motions of the polyhedron with respect to a Conventional Inertial (coordinate) System (CIS), i.e., those motions that are common to all stations such as precession, nutation, earth orientation (earth rotation and polar motion) but primarily the latter. The second function is to monitor the internal motions (or deformations) of the polyhedron, i.e., those motions that are not common to all stations such as plate tectonic motion, crustal deformation, tidal motions and ocean loading. Thus, the deformation of the polyhedron will be defined as having no common rotations or translations [Mueller, 1981; Bender and Goad, 1979; Bender, 1981; Guinot, 1981]. These two functions allow a convenient and practical division of the CTS into an earth orientation monitoring service and an earth deformation monitoring service, although the two are integrally related.

2.12 Definition of the CTS

The frame of the CTS is defined by the adopted coordinates of a global network of stations at a fundamental epoch of time, t_0, which constitutes the vertices of a fundamental polyhedron. Denote these fundamental coordinates by X_{t_0}. They will be estimated from an observational campaign dedicated to this purpose in which a combination of several modern three-dimensional geodetic systems will participate. The estimation of X_{t_0} by a coordinate transformation combined with a free adjustment approach is described in [Bock, in preparation].

The fundamental polyhedron establishes a geometric description of the earth's crust at the fundamental epoch, and therefore serves as a reference frame for the monitoring of earth dynamics. In addition, the CTS will include all necessary model parameters so that the system will be well-defined and unambiguous. These include precession (P) and nutation (N) models to be used in connecting the CIT and CTS according to

$$[CTS] = SNP\,[CIS]$$

where S will be estimated by the earth orientation monitoring service relative to the initial orientation of the fundamental polyhedron at t_0. In addition, tidal models, plate tectonic models, etc. will be incorporated in maintaining the system as well as other fundamental parameters such as the speed of light.

The fundamental polyhedron is aligned with the CIO-BIH system at t_0 as described in [Bock, in preparation]. However, since the earth can no longer be assumed to be rigid, the new CTS must be referred to a set of axes that are fixed in some average sense in the deformable earth. A modified Tisserand axes definition will serve this purpose. It can be shown that the algorithms used to maintain the CTS are equivalent to this definition and therefore consistent with earth rotation theory.

2.121 Tisserand axes.

For the deformable earth, no body-fixed reference axes exist. In earth rotation theory usually Tisserand's axes are used.

From the definition of the Tisserand axes, the relative angular momentum should be zero [Moritz, 1980]

$$\underline{h} = \iiint \underline{x} \wedge \underline{u}\, dm = 0 \tag{1}$$

According to [Jeffreys, 1970]

$$\iiint \underline{u}^2\, dm = \min \tag{2}$$

where $\underline{u}$ is the velocity vector.

From (1) and (2) we obtain

$$\begin{aligned}
&\iiint (u_y \cdot z - u_z \cdot y)\, dm = 0 \\
&\iiint (u_z \cdot x - u_x \cdot z)\, dm = 0 \\
&\iiint (u_x \cdot y - u_y \cdot x)\, dm = 0 \\
&\iiint u_x\, dm = 0 \\
&\iiint u_y\, dm = 0 \\
&\iiint u_z\, dm = 0
\end{aligned} \tag{3}$$

The integrals are on the whole earth body; thus Munk and MacDonald call these axes "Tisserand's mean axes of body." Very roughly we can think that these axes are "fixed" in some average sense in the deformable earth. They are ideal axes and can hardly be realized in practice, since within the earth the velocity u is impossible to measure directly by geodetic means.

2.122 Approximate realization of the Tisserand axes (ATA).

First, we alter the volume integrals into surface integrals. This approximation is dynamically drastic. Because of this approximation any motion of the crust as a whole relative to mantle could not be detected. But this approximation is practically necessary for geodetic purposes. We call these modified axes the "Tisserand mean axes of crust." Or roughly, we think these axes will be "fixed" in some average sense in the deformable earth crust.

Second, the velocity vector is changed into a movement (deformation) vector. For an infinitesimal time interval, this change is rigorous. For a finite time interval, it is an approximation.

Third, we use summation instead of integrals. The points to be summed should be infinite and cover all the earth's crust.

Last, for practical reasons, only finite points are available, and they are only on solid earth surface, not on ocean.

After these approximations, the requirements for Tisserand axes become

$$
\begin{aligned}
&\sum_{i=1}^{n} (\Delta y \cdot z - \Delta z \cdot y)_i \, M_i = 0 \\
&\sum_{i=1}^{n} (\Delta z \cdot x - \Delta x \cdot z)_i \, M_i = 0 \\
&\sum_{i=1}^{n} (\Delta x \cdot y - \Delta y \cdot x)_i \, M_i = 0 \\
&\sum_{i=1}^{n} \Delta x_i \, M_i = 0 \\
&\sum_{i=1}^{n} \Delta y_i \, M_i = 0 \\
&\sum_{i=1}^{n} \Delta z_i \, M_i = 0
\end{aligned}
\qquad (4)
$$

These equations are used for practically defining and maintaining the new CTS. To make such defined CTS meaningful, a large number of well distributed stations are needed. If the stations are not well distributed and some stations are located in areas less stable than others, the weight matrix $\underline{M}$ can be used. Otherwise, let $\underline{M} = \underline{I}$.

2.123 Other proposed constraints for the maintenance of the CTS.

Some authors proposed that the constraints for the maintenance of the CTS should be that there is no common rotation (and translation) in the deformation (see [Mueller, 1981; Bender, 1979, 1981; Guinot, 1981]). Now we show that the ATA also fulfills the above requirement of no common rotation or translation.

Let $\Delta\underline{x}_t^j$ be the deformation of station j at time t.

$$\Delta\underline{x}_t^j = \underline{x}_t^j - \underline{x}_o^j \tag{5}$$

Imagine that at time t, station coordinates change from $\underline{x}_o^j$ to $\underline{x}_t^{j'}$. Through a translation and a rotation $\underline{x}_t^{j'}$ is changed into $\underline{x}_t^j$, so that $\sum_j |\underline{x}_t^j - \underline{x}_o^j|^2 \cdot w_j = \min$, where w_j is the "weight." In other words, by doing so, $\underline{x}_t$ will have no common rotation or common translation with respect to $\underline{x}_o$. Let $R(\underline{\theta})$ be the rotation and $\delta\underline{x}$ be the translation. Then

$$\underline{x}_t^j = R(\underline{\theta}) \cdot \underline{x}_t^{j'} - \delta\underline{x} \tag{6}$$

$$\Delta\underline{x}_t^j = \underline{x}_t^j - \underline{x}_o^j = R(\underline{\theta}) \cdot \underline{x}_t^{j'} - \delta\underline{x} - \underline{x}_o^j \tag{7}$$

Form

$$s = \sum_j w_j \, |\Delta\underline{x}_t^j|^2 \tag{8}$$

By

$$\frac{\partial s}{\partial \underline{\theta}} = 0, \qquad \frac{\partial s}{\partial \delta\underline{x}} = 0 \tag{9}$$

we obtain the six constraints.

In a Cartesian coordinate system, equation (9) becomes

$$\Sigma\, w_j \cdot \Delta X_j = \Sigma\, w_j\, \Delta Y_j = \Sigma\, w_j\, \Delta Z_j = 0 \tag{10a}$$

$$\Sigma\, w_j (\Delta Y \cdot Z - \Delta Z \cdot Y)_j = \Sigma w_j (\Delta Z \cdot X - \Delta X \cdot Z)_j = \Sigma w_j (\Delta X \cdot Y - \Delta Y \cdot X)_j = 0 \tag{10b}$$

Equations (10) are exactly the same form as equation (4) for ATA requirements.

For the geodetic coordinate system (H, ϕ, λ), the above equation changes into

$$\Sigma\, w_j(-R\cos\phi\,\sin\lambda\,\Delta\lambda - R\sin\phi\,\cos\lambda\,\Delta\phi + \cos\phi\,\cos\lambda\,\Delta H)_j = 0$$

$$\Sigma\, w_j(R\cos\phi\,\cos\lambda\,\Delta\lambda - R\sin\phi\,\sin\lambda\,\Delta\phi + \cos\phi\,\sin\lambda\,\Delta H)_j = 0 \tag{11a}$$

$$\Sigma\, w_j(R\cos\phi\,\Delta\phi + \sin\phi\,\Delta H)_j = 0$$

$$\Sigma\, w_j(\cos\phi\,\sin\phi\,\cos\lambda\,\Delta\lambda - \sin\lambda\,\Delta\phi)_j = 0$$

$$\Sigma\, w_j(\cos\phi\,\sin\phi\,\sin\lambda\,\Delta\lambda + \cos\lambda\,\Delta\phi)_j = 0 \tag{11b}$$

$$\Sigma\, w_j(\cos^2\phi\,\Delta\lambda)_j = 0$$

For the local horizon coordinate system where x points east, y north, z upward, neglecting the earth's flattening, the constraints are

$$\Sigma\, w_j(-\sin\lambda\,\Delta x - \sin\phi\,\cos\lambda\,\Delta y + \cos\phi\,\cos\lambda\,\Delta z)_j = 0$$

$$\Sigma\, w_j(\cos\lambda\,\Delta x - \sin\phi\,\sin\lambda\,\Delta y + \cos\phi\,\sin\lambda\,\Delta z)_j = 0 \tag{12a}$$

$$\Sigma\, w_j(\cos\phi\,\Delta y + \sin\phi\,\Delta z)_j = 0$$

$$\Sigma\, w_j(\sin\phi\,\cos\lambda\,\Delta x - \sin\lambda\,\Delta y)_j = 0$$

$$\Sigma\, w_j(\sin\phi\,\sin\lambda\,\Delta x + \cos\lambda\,\Delta y)_j = 0 \tag{12b}$$

$$\Sigma\, w_j(\cos\phi\,\Delta x)_j = 0$$

Equations (12b) are the same as given by Bender and Goad [1979].

These constraints also require a sufficient number of well-distributed stations. It is hoped that there is no common rotation (or translation) with respect to the whole earth crust. If there are not enough stations and/or they are ill distributed, then these station deformations do have some common motion. Using these constraints to eliminate the common motion in the deformations will bring the true common motion into the determined polar motion. That is, we cannot separate the stations' common motion from real polar motion.

When a sufficient number of well-distributed stations are available, the CTS defined and maintained by these contraints are ATA, and at the same time it fulfills the condition of "no common rotation and no common translation."

2.124 Dimension of the new CTS.

The CTS's of different observing techniques have different dimensions, depending on the observables and also on the coordinate system of the observing targets (CIS).

Techniques:	Optical	VLBI	LR, GPS, Doppler
CIS:	2-dimensional on unit sphere	Same as optical	3-dimensional
Observables:	Angle	Distance (time)	Distance (time)
CTS:	2-dimensional on unit sphere	Quasi-3-dimensional	3-dimensional

For VLBI the observable is distance so that the CTS built by VLBI is three-dimensional, but the source position is two-dimensional (on a unit sphere). Therefore, the VLBI CTS is not fully three-dimensional. One can only determine distance and shape, but not the center of the coordinate system. We call it quasi-three-dimensional. The new CTS seems to be the combination of a few new techniques. Therefore the new uniform CTS is three-dimensional. It seems insufficient to define a three-dimensional new CTS only by longitude origin and pole position.

2.125 Sensitivity of the rotation with the height change.

In a Cartesian coordinate system, a small rotation $\underline{\theta}$ and a translation $\underline{\delta}$ will change the coordinates in such a way

$$\begin{aligned} \Delta X_i &= \theta_3 Y_i - \theta_2 Z_i + \delta X \\ \Delta Y_i &= \theta_1 Z_i - \theta_3 X_i + \delta Y \\ \Delta Z_i &= \theta_2 X_i - \theta_1 Y_i + \delta Z \end{aligned} \tag{13}$$

The corresponding height change is

$$\Delta h_i = \frac{\Delta Z_i \cdot Z_i + \Delta Y_i \cdot Y_i + \Delta X_i \cdot X_i}{\sqrt{X_i^2 + Y_i^2 + Z_i^2}} \tag{14}$$

If only a small rotation exists, that is, $\underline{\delta} = 0$, then we will find

$$\Delta h_i \equiv 0 \tag{15}$$

It means that the rotation change only causes horizontal coordinate changes. The height is not sensitive to rotation change. The above result is exactly as stated by [Bender and Goad, 1979].

But the height being insensitive to rotation does not necessarily mean that rotation is also insensitive to height change. On the contrary, we now prove that rotation is sensitive to height changes (in the practical station distribution).

Now the question is to solve for $\underline{\theta}$ and $\underline{\delta}$ from the height change by equation (13). In this case a least squares method can be used. The normal equation is

$$N \times B = U \tag{16}$$

where

$$N = \begin{bmatrix} [Z^2+Y^2] & -[XY] & -[XZ] & 0 & [Z] & -[Y] \\ & [X^2+Z^2] & -[YZ] & -[Z] & 0 & [X] \\ & & [X^2+Y^2] & [Y] & -[X] & 0 \\ & & & n & 0 & 0 \\ & \text{symmetric} & & & n & 0 \\ & & & & & n \end{bmatrix}$$

$$B = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \delta X \\ \delta Y \\ \delta Z \end{bmatrix} \qquad U = \begin{bmatrix} [\Delta Z \cdot Y - \Delta Y \cdot Z] \\ [\Delta X \cdot Z - \Delta Z \cdot X] \\ [\Delta Y \cdot X - \Delta X \cdot Y] \\ [\Delta X] \\ [\Delta Y] \\ [\Delta Z] \end{bmatrix} \tag{17}$$

For the practical station distribution, the nondiagonal elements in N generally are not equal to zero. We write N^{-1} as

$$N^{-1} = [a_{ij}]$$

Now we transform the above equation from the Cartesian to the local horizon system, and letting $\Delta\phi = \Delta\lambda = 0$, then

$$U = \begin{bmatrix} 0 \\ 0 \\ 0 \\ [\Delta h \cos\phi \cos\lambda] \\ [\Delta h \cos\phi \sin\lambda] \\ [\Delta h \sin\phi] \end{bmatrix} \tag{18}$$

$$\theta_i = a_{i4}\,[\Delta h \cos\phi \cos\lambda] + a_{i5}[\Delta h \cos\phi \sin\lambda] + a_{i6}[\Delta h \sin\phi] \qquad i = 1,2,3 \tag{19}$$

Since a_{i4}, a_{i5}, a_{i6} generally are not equal to zero, θ_i also is not equal to zero. Simulation shows that θ_i can be of the same order of magnitude as Δh. That means that rotation is sensitive to height change.

In equations (10), (11) and (12) we deliberately divide the constraints into two groups: (a) for translation, (b) for rotation, although for practical reasons people seem to be more interested in rotation than in translation. However, through the above derivation we see that height change will, through translation, influence rotation. Since the CTS is three-dimensional, the six constraints are a complete set, and we could not use only set (b), even if we are only interested in rotation.

2.13 Maintenance of the CTS

2.131 General Description.

The primary functions of the CTS are twofold. First, to monitor the variations in earth orientation relative to the fundamental epoch and second to monitor earth deformation. The first function will require a dedicated network of observations on a continuous basis considering the requirements of one-day earth rotation and two-day polar motion averages to 5 cm accuracy. The second function does not require such an intense observational schedule since it is anticipated that the time variation of the polyhedron coordinates due to deformations will be in the submeter range per year considering plate tectonic theory [Minster et al., 1974, 1978]. In addition, solely due to economic and other practical considerations, we could not expect all the CTS stations to observe continuously. Furthermore, the first function requires dedicated fixed observations while the second function may also involve incorporating mobile stations.

We propose the following setup for the CTS as is depicted in Fig. 1.

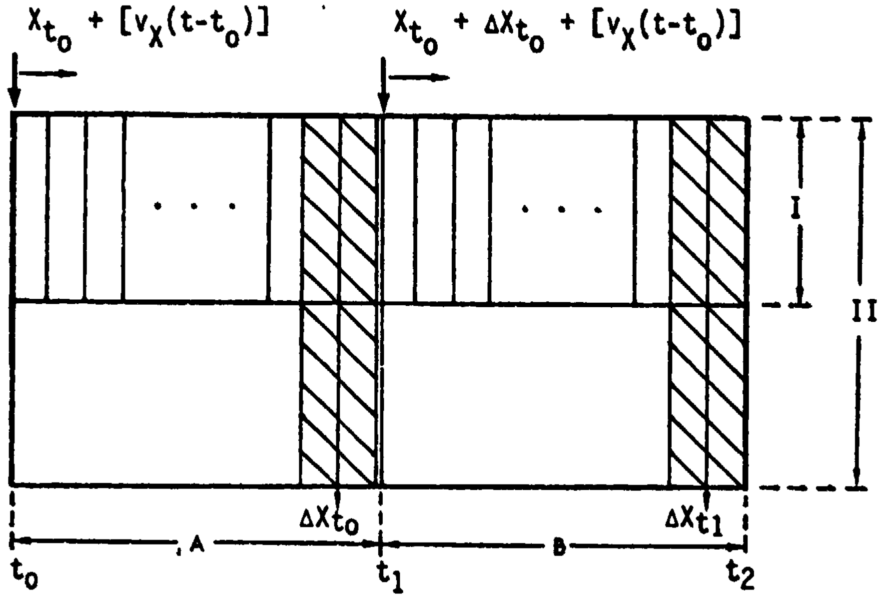

Fig. 1 Schematic CTS operations.

The polyhedron is composed of a set of stations distributed (in a manner described in [Bock, in preparation]) globally. In the figure, we see an observation schedule divided into two total intervals, $A(t_1-t_0)$ and $B(t_2-t_1)$. Level I, the Earth Orientation Monitoring Service, is composed of a dedicated subset of the CTS. These stations monitor earth orientation on a regular basis denoted by the subintervals within the total intervals. These results are made available to the user community as is done by the earth orientation services today. Level II, the Earth Deformation Monitoring Service, is composed of all the polyhedron stations which at the end of each total interval observe together in one short campaign (denoted in the figure by the shaded portion). It seems evident that observations from a larger number of stations, distributed over several of the larger tectonic plates will provide a better representation of the deformation of the earth than would the observations from the limited (due to economic and practical considerations) number of stations of Level I. From the Level II solution which will basically have the same parametrization as Level I, the baseline chord lengths will be extracted along with their covariance matrix. These will be used as input for a generalized free adjustment solution (to be described in [Bock, in preparation] to estimate corrections to the polyhedron coordinates due to deformations. For example, as shown in the figure, at the end of interval A, the Level II solution will yield ΔX_{t_0} which will be added to the fundamental coordinates, to be used as input in interval B. In this way, we prevent the internal deformations of the polyhedron from contaminating the global rotation parameters and we keep the CTS referred to a set of axes that are fixed in an average sense in the deformable earth. The procedure is repeated for each total interval in the same manner as depicted in the figure. It should be mentioned that the polyhedron coordinates may also be corrected, as shown in the figure, by $v_X(t-t_0)$ where v_X (the time variation of the coordinates) is derived from a geophysical model adopted by the CTS, if an accurate enough model is available. This aspect is discussed in [Bock, in preparation].

2.132 Level I - Earth Orientation Monitoring Service

The following discussion is restricted to VLBI observations since it is felt that the Earth Orientation Monitoring Service will be composed primarily of dedicated VLBI observatories. This measurement system has distinct advantages over the other techniques. VLBI measurements are independent of the gravity field of the earth making them essentially geometric in nature. Furthermore, the system has virtually all weather capability. Most important, VLBI has greater sensitivity to earth orientation parameters than do satellite laser observations particularly in UT1-UTC variations [Van Gelder, 1978].

The VLBI mathematical models for delay and delay-rate observations are described in detail in [Robertson, 1975; Ma, 1978]. For the purpose of this discussion we will follow the notation of [Bock, 1980].

The choice of parameters is particularly important in the earth orientation solution (Level I) since all earth orientation parameters need to be related unambiguously to the initial orientation of the fundamental polyhedron given by X_{t_0} which has been made to coincide with the CIO-BIH system at the fundamental epoch, t_0. As shown in [Bock, 1980], the earth orientation parameters (ξ_0, η_0, κ_0) and the baseline coordinate differences are inseparable since the initial orientation of the terrestrial frame is not sensed by the observables. In practice, this dependency is broken by not parametrizing earth orientation over, say, the first day of observations of a particular observation campaign. Subsequently, three earth orientation parameters are estimated over so-called earth orientation steps, each step spanning a certain period of time [Dermanis, 1977]. Thus, the earth orientation parameters (ξ_ℓ-ξ_0, η_ℓ-η_0, κ_ℓ-κ_0) are average values over each step relative to (ξ_0, η_0, κ_0) which is input into the adjustment and used over the first step. However, as shown in [Bock, 1980] any errors in the initial orientation assumed for the first step biases the estimates of coordinate differences (or coordinates if in addition one station is fixed as is usually done in practice) making

this parametrization particularly unsuitable for the maintenance of a CTS. It is, furthermore, difficult to relate the orientation origin of different data sets. In addition, the fixing of the first step is done in a subjective manner and the resulting parameter estimates are influenced by the length of the step and distribution of observations over that step.

The only geodetic parameters estimable from a polyhedron of VLBI stations are the size and shape of the polyhedron, i.e., the baseline chord lengths and the orientation of the polyhedron with respect to the fundamental polyhedron given by three rotation angles. Thus, by parametrizing baseline chord lengths and rotation angles we can avoid the bias introduced by fixing a step since in this case it is no longer necessary to fix one. After all, baseline lengths are invariant with respect to coordinate system definition. By introducing as input into the adjustment X_{t_0} (corrected for polyhedron deformation), the three rotation angles (ξ, η, κ) per step always refer to the fundamental orientation of the polyhedron, unambiguously.

The partial derivatives of the design matrix for the VLBI adjustment are given in [Bock, 1980]. The contribution to the design matrix for baseline chord length, B_{ij}, is given by

$$A_{B_{ij}} = (A_{\Delta X_{ij}} \Delta X_{ij} + A_{\Delta Y_{ij}} \Delta Y_{ij} + A_{\Delta Z_{ij}} \Delta Z_{ij})/B_{ij}$$

where A denotes the partial derivative of the observables (delay) with respect to the subscripted parameter (see [Bock, 1980; Bock, in preparation]).

It should be mentioned that the baseline chord lengths propagated from the estimation of coordinates (or coordinate differences) are unaffected by errors in ξ_0, η_0, κ_0 fixed over the first step. However, this type of adjustment is less rigorous because of an arbitrary fixing of the first step to provide the necessary minimal constraints. Our proposed solution involves only the strictly estimable quantities, i.e., there is no need for any constraints except for at least one source right ascencion to fix the origin of the inertial frame. However, any error in this value, $d\alpha_0$, will not

propagate into baseline lengths or polar motion but only into κ, the earth rotation parameter. By being consistent with the origin choice (α_0), i.e., adopting a fundamental source catalogue (CIS), this error is essentially eliminated. As far as parametrizing radio -source coordinates (α, δ), it is probably best to hold these fixed according to the fundamental coordinates of a source catalogue, and updated to the time-of-observation epoch.

2.133 Level II - Earth Deformation Monitoring Service

In the analysis of earth deformation, all CTS stations observe according to a specified schedule, to be described in [Bock, in preparation], the point being that the observational period is short and infrequent. In contrast to Level I, the emphasis is on the estimation of baseline lengths (rather than earth orientation) as a key to the analysis of the deformations of the polyhedron with time. Thus, any of the systems that provide accurate baseline lengths can participate.

The estimation of earth deformation proceeds in two steps. First, the observations of the Level II campaign are analyzed as in Level I except that the input prarameters for the station coordinates are held at X_{t_0}, possibly corrected for the motions inferred by an adopted geophysical model as described in [Bock, in preparation]. In this way, the connection to the fundamental polyhedron is maintained. The parameters that are estimated in the first step are the same as in Level I--baseline chord lengths, earth orientation angles (in order to remove all common rotations) and model parameters.

For the second step, the estimated baseline lengths as well as their estimated covariances are extracted from the first step adjustment. From this information, the size and shape of the deformed polyhedron is completely defined, assumed constant over the short observational campaign. However, the absolute location of the polyhedron, i.e., its new coordinates are undetermined by the change of its sides, but this is exactly what we seek. The problem is singular, being rank deficient by 6, the familiar origin and orientation defects. In order to overcome this singularity we will employ a

free adjustment approach generalized to include an a priori geophysical model for the time variations of the polyhedron vertices. It will be shown that this method insures that the CTS axes are fixed in the sense of the modified Tisserand axes definition, in the deformable earth. Furthermore, it will be shown that the estimation method yields parameters with optimal statistical and geometric properties. This approach has been applied to crustal deformation analyses (see [Brunner, 1979; Brunner et al., 1980]) and has been suggested by [Dermanis, 1980; Bender and Goad, 1979; Bender, 1980] for application to terrestrial reference frames although in a less general and detailed manner than will be presented in [Bock, in preparation].

2.134 Some comments about the practical realization of the new CTS.

For some conventional reason, we want the new CTS to be the continuation of the BIH system. Let t_0 be the epoch for alignment. This means that at epoch t_0 the z-axis of the new CTS will coincide (within the scope of error) with the BIH-CIO pole. Therefore, the new CTS generally cannot be Tisserand axes at time t_0, even in the approximation point of view. By applying the six constraints we keep the relative position between the CTS and the Tisserand axes at any time t the same (approximately) as at time t_0, so that the polar motion (earth rotation) in CTS is the same as that in the Tisserand axes.

As stated before, we must have a large number of well-distributed stations to make these constraints meaningful. By deformation we generally mean the secular or long-period deformation. For economical reasons, we could not ask all the CTS stations to observe continuously through the year; only once in a while is necessary and possible. On the other hand, the earth rotation service stations need continuous observation. Therefore, we can select a number of CTS stations to be the service stations. Since these service stations' deformations are determined by the process of CTS maintenance, their distribution only should be optimal for earth station parameter determination.

2.135 Ongoing investigations.

The algorithms for both Level I and Level II are being tested by simulations as well as with real data. An error analysis will be performed for earth orientation and deformation parameter estimation. In addition, optimal design questions such as CTS station distribution, observation regularity and scheduling will be investigated.

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2.14 Comparison of Polar Motion Data from the 1980 Project MERIT Short Campaign

(presented at IAU Colloquium No. 63 on "High Precision Earth Rotation and Earth-Moon Dynamics: Lunar Distances and Related Observations," May 22-27, 1981, Grasse, France)

1. INTRODUCTION

The short campaign of MERIT (a program of international collaboration to Monitor Earth Rotation and Intercompare the Techniques of observation and analysis) was held during the three-month period August to October, 1980. The participation was quite extensive and varied in techniques: 82 instruments from 22 countries provided classical astrometric data; the U.S. Defense Mapping Agency and GRGS (France) through the MEDOC network supplied Doppler satellite observations; 900 passes of Lageos and 780 passes of Starlette were observed from as many as 27 laser ranging stations and analyzed by SAO (Smithsonian Astrophysical Observatory, Cambridge, Mass.), CNES (Centre National d'Etudes Spatiales, Toulouse, France), UTX (University of Texas at Austin), and GSFC (NASA Goddard Space Flight Center, Greenbelt, Md.). Comparison of the above data set is the subject of this paper. Additional observations were made by connected-element radio interferometry at Green Bank, W.Va., and at Cambridge, U.K.; very long baseline radio interferometry at about ten stations around the world; lunar laser ranging at the McDonald Observatory, Texas. Data from these techniques is not included in this comparison because they either did not provide continuous data throughout the campaign, or the data was not readily available through the Coordinating Center at the BIH in Paris.

2. PREDICTION OF POLAR MOTION

Based on the analysis of polar motion behavior, the possibility of predicting polar motion for a long time interval (1-2 years in advance) with sufficient accuracy has been found. The best estimated Chandler period is taken as constant, and six years of data are used to estimate the amplitudes, phases and ellipticity of the Chandler and annual motions. These estimated parameters are then used to predict the next year's (or next two years') polar motion. In making the prediction, possible linear trends are also taken into consideration.

The data used for prediction were those of the BIH, IPMS and DMA, from 1968 to 1980 (DMA from 1972 to 1980). Polar motions have been predicted for one year in advance and compared to smoothed observed ones: the mean rms of the differences (predicted minus observed) is about 0"02. Differences between relative polar motions are much smaller: for a time interval of 20-30 days, the rms difference is about 0"01 (30 cm) through the whole year. Compared with the best available VLBI results (from 1977 to 1980), the rms difference is only 0"013; and the rms difference of the relative polar motions (with time interval less than or equal to two months) is 0"008, both values being remarkably small.

The predicted polar motion can be used for geodetic purposes. It seems that the accuracy of the prediction is high enough for any practical purpose that requires real time polar motion up to an accuracy of, say, 50 cm. This would include rather sophisticated applications such as control of space probes. Details may be found in "Prediction of Earth Rotation and Polar Motion," Dept. of Geodetic Science Rep., Ohio State Univ. (in press).

3. MERIT DATA INTERCOMPARISON BASED ON RAW DATA

The BIH has already analyzed the MERIT data using BIH Circular D as a reference. Since new techniques are expected to obtain better accuracies than now available from the BIH, it was thought that a mutual comparison may be more rational than using Circular D as a common reference. Both raw data and smoothed data were used.

3.1 Absolute Comparison

The standard errors of the polar coordinate differences of each two Analyzing Centers were computed in all combinations with the following results:

	$\sigma_{\Delta x}$	$\sigma_{\Delta y}$	mean
DMA - MEDOC	0".040	0".044	0".042
CNES(Lageos) - CNES(Starlette)	0.031	0.053	0.042
SAO - CNES(Starlette)	0.040	0.036	0.038
Astrometry - SAO	0.022	0.025	0.024
Astrometry - DMA	0.022	0.025	0.023
Astrometry - UTX	0.019	0.026	0.023
DMA - SAO	0.010	0.011	0.011
UTX - SAO	0.014	0.012	0.013
UTX - DMA	0.014	0.010	0.012
SAO - CNES(Lageos)	0.009	0.014	0.012
UTX - CNES(Lageos)	0.010	0.017	0.014
SAO - Circular D	0.009	0.009	0.009
UTX - Circular D	0.011	0.013	0.012

From the above values it is suggested that the standard errors are approximately 0".04 for MEDOC and for CNES(Starlette); 0".02 for classical astrometry; 0".008 - 0".01 for SAO, DMA, UTX and CNES(Lageos).

3.2 Relative (Variation of Polar Motion) Comparison

Relative polar motion comparison is used to detect possible systematic errors (other than a constant due to the difference of origins). Systematic errors will most likely be smaller in relative polar motion.

The standard deviations of polar motion variations are given below.

	$\sigma_{\delta\Delta x}$	$\sigma_{\delta\Delta y}$	mean
DMA - MEDOC	0".039	0".039	0".039
UTX - SAO	0.010	0.010	0.010
UTX - DMA	0.014	0.008	0.011
DMA - SAO	0.010	0.009	0.010
Astrometry - SAO	0.017	0.022	0.020
Astrometry - DMA	0.024	0.022	0.023
Astrometry - UTX	0.017	0.024	0.021
SAO - Circular D	0.005	0.004	0.005
UTX - Circular D	0.011	0.010	0.010

Since every $\sigma_{\Delta x}$ is more or less larger than $\sigma_{\delta\Delta x}$, it appears that there may be systematic errors among the Analyzing Centers.

4. MERIT DATA INTERCOMPARISON AFTER SMOOTHING

The above comparisons gave reason to expect systematic differences between the results of the earth rotation parameters as obtained from different techniques. A smoothing process was attempted to find the proper-

ties of these differences in terms of the amplitudes of the Chandler ($\sqrt{k_2^2 + k_3^2}$) and annual motions ($\sqrt{k_4^2 + k_5^2}$) and the centers of the polhodes (k_1 and k_6), using the following well known circular model:

$$x = k_1 + k_2 \cos A + k_3 \sin A + k_4 \cos C + k_5 \sin C$$

$$y = k_6 - k_2 \sin A + k_3 \cos A - k_4 \sin C + k_5 \cos C$$

where $A = 2\pi$ (MJD - 42413)/365 (annual frequency)
$C = 2\pi$ (MJD - 42413)/435 (Chandler frequency)

These coefficients are listed in Table 1 together with their predicted values obtained as explained in Section 2. The values of coefficients k_1 and k_6 were plotted on a graph with their standard deviations (see figure). They correspond to the x and y coordinates of the centers of the circles depicting the pole movement. This figure shows that systematic differences may exist in the pole origin. The tabulated amplitudes of the annual and Chandler motions indicate the same thing. The agreement between the predicted and SAO values is truly remarkable.

The relatively large standard deviations and the shortness of the data span naturally cast a shadow of doubt on the validity of these coefficients. For this reason another adjustment was performed in which the amplitudes of the Chandler and annual motions (coefficients k_2 - k_5) were constrained to their predicted values and only the coordinates of the polhode centers (k_1 and k_6) were computed. The results are in the last two columns of Table 1 and in view of the preliminary data set the agreement is remarkable. There seems to be very little evidence of systematic differences in the pole origin.

5. CONCLUSION

The data available for the MERIT Short Campaign as expected was not really sufficient to enable us to arrive at conclusive evidence regarding the systematic differences and their estimation. The noise level was also quite high; thus the importance of the intercomparison of data to be made available through the MERIT Main Campaign cannot be overemphasized.

All results in this paper were based on the data distributed during the campaign by the Coordinating Center at the BIH except for the GSFC data.

2.2 Utilization of Range-Difference Observations in Geodynamics

2.21 Utilization of Simultaneous Lageos Range-Differences in Geodynamics

Introduction

A summary of the research completed under this project, was presented in the 4th Lageos Working Group Meeting, held at NASA-GSFC (September 1-2,1981). The presentation is summarized in Appendix . In the following sections we elaborate on some theoretical questions that we feel to be of major importance in understanding the need for developing the simultaneous range-differencing technique. A number of preliminary results obtained from a very small data set are also discussed.

2.211 Estimability of the polar motion step function.

It has been well established by now (e.g., [Van Gelder,1978]) that the coordinates of the pole are inseparable from the observing station positions; a change in one can be attributed to either of the two. We therefore seek for a way to circumvent this deficiency and uncouple the two parameters. In [ibid.], the idea of determining variations in the motion of the pole has been proposed, instead of absolute polar coordinates. Even in this case however, the variations are only "conditionally estimable," the reason being that an origin, with respect to which the variations are referenced, must still be enforced and obviously the bias on this initial position affects the estimated variations. Fortunately, translational biases do not contaminate the solution, but a rotation of the coordinate system (coming from errors in UT1-UTC values) does affect the pole variations. This error is expected to be insignificant though, considering that even with present capabilities the errors in UT1 are no greater than 1 ms. We assume that this bias can be tolerated and we proceed to establish a method by which the initial position information will be introduced in the estimation process.

2.212 Discussion of the estimation process.

There are various ways of introducing the definition for the system of coordinates of the pole, each having its own intricacies, while still maintaining the continuity with the present BIH-1979 system. We could rotate the station positions for instance into the modified terrestrial system which has its Z-axis coincident with the mean position of the instantaneous pole over the first step or its position at the beginning of our campaign. We assume the coordinates of the stations fixed to

these values (except for systematic effects, e.g., tides,etc. for which we correct a priori) and we therefore only solve for the coordinates of the pole which are nothing else but the variations with respect to the adopted initial pole position. This method is simple in concept, but has the distinct and undesirable disadvantage that any biases from the station coordinates will propagate into the pole position directly.

On the other hand, we could solve for the positions of the pole and the ground stations simultaneously (except for an origin of longitude definition), provided that we assume the position of the pole over the initial step is perfectly known. In this sense, the variations of the pole at each subsequent step will refer to this initially adopted position. The station coordinates which are being adjusted simultaneously, must be primarily determined from the observations on the initial step. This ofcourse indicates that the duration of the initial step as well as the amount and distribution of the data over that period, will be crucial in defining the initial orientation of the ground network. It goes without saying that long gaps in the data record cannot be tolerated in this scenario, since the quality of the solution strongly relies on a geometrically sound satellite-observer configuration.

It is obvious by now that since we are using quasi-simultaneous range-differences which reduce by a large percentage the amount of usable data and that, in addition to this, optimal configuration requirements further reduce this amount, we have to have very high quality data or the accuracy of our estimates will be very poor. It is anticipated therefore, that if this technique is adopted for continuous monitoring of the motion of the pole, the observing schedule of the participating stations should be coordinated in such a way that all possible Lageos passes are coobserved when possible and that redundant baseline pairs are included in the network to compensate for data loss from poor weather, station breakdowns and satellite observability problems.

The two approaches outlined above are quite similar in the way that the origin and orientation of the polar coordinate system is defined. In the first case the bias in the definition will come from the adopted initial position of the pole plus any unaccounted for station motions since we are not solving for their positions. In the second case, however, the coordinates of the stations are adjusted to fit the data as well as the initially adopted pole position. It is therefore obvious that any unfavorable data distribution or poor data quality during the initial step, will directly affect the estimated pole variations. Moreover, the station coordinate system definition changes from one solution to the next, in a rather uncontrollable manner, so that not only the orientation of the two systems is biased (provided by the estimated pole variations), but the origin

definition itself.

Since none of the above procedures will produce the level of accuracies that we are after, we must devise a different approach where the effects of the aforementioned control factors will be either eliminated or at least kept below tolerance levels. The method proposed here is the following.

A set of consistent station positions for the monitoring observatories is obtained initially from a long arc (5-6 years) of Lageos data. The simultaneously obtained satellite ephemeris defines a quasi-inertial system (dynamical CIS), which is linked to the terrestrial system via an adopted set of precession, nutation and polar motion models, the latter being possibly the BIH system so that continuity is preserved. Once this master set of station positions and the satellite ephemeris have been obtained, the changes of the station positions are monitored with respect to the evolving satellite ephemeris (for which we do not adjust anymore). The discrepancies in the adjustment are attributed to the variations of the position of the pole. The advantage of this system over the ones previously described is that in this case the original relationship between the inertial and the terrestrial system is being preserved within the bounds of observational accuracy. Furthermore, since the terrestrial system has been defined on the basis of a long data record, any biases coming from the polar motion model used in the reduction should average out.

2.213 Orbital bias elimination by range-differencing.

The force model that governs the motion of a satellite is not perfectly known and so its inadequacies will contaminate the pole positions. If though quasi-simultaneous ranging is used, the orbital model inadequacies will have little effect on the results. In fact to understand how this is achieved, let us assume that our data set consists of two subsets of ranges where each range in the first set L , has been obtained simultaneously with the corresponding range in the second set L . The range-difference data set is therefore :

$$L = L_2 - L_1 \tag{1}$$

Based on the satellite ephemeris and station positions, a set of computed range-differences is obtained. The comparison of these to the observed ones during the estimation process will, ofcourse, result in adjusting the pole position to fit the data and therefore estimate its motion. Assume now that for each position of the satellite, the orbital model introduces a bias b in the computation of the range. This bias is not the same at each instant but this need not concern us for the time since the

ranges are differenced only at corresponding epochs. The computed function values (ranges) can be separated into two components; one which is the value they would have if the bias were not there, (L^T_1, L^T_2), and the bias itself (b_1, b_2) :

$$L^C_1 = L^T_1 + b_1 \tag{2}$$

and

$$L^C_2 = L^T_2 + b_2 \tag{3}$$

The equivalent for range-differences then is :

$$L^C_{RD} = L^C_2 - L^C_1 \tag{4}$$

or

$$L^C_{RD} = L^T_2 - L^T_1 + b_2 - b_1 \tag{5}$$

If the bias for each pair of ranges were the same, then b =b and the resulting computed differences are bias-free. Unfortunately though, this cannot be assumed since different model deficiencies have different effects on the satellite orbit and then depending on the relative location of stations and satellite positions these biases propagate in a different manner in the computation.

To minimize these biases one possibility is to apply the differencing one more time. By differencing consecutive range-differences these biases almost disappear since their behavior cannot change significantly over the short interval (a few seconds) between two consecutive observations. So if for the ith range-difference :

$$\ell^C_{RD_i} = \ell^T_{2i} - \ell^T_{1i} + (b_2 - b_1)_i \tag{6}$$

and for the ith+1 :

$$\ell^C_{RD_{i+1}} = \ell^T_{2i+1} - \ell^T_{2i+1} + (b_2 - b_1)_{i+1} \tag{7}$$

then the double difference is :

$$\ell^C_{DD_i} = \ell^C_{RD_{i+1}} - \ell^C_{RD_i} \tag{8}$$

or

$$\ell^{C}_{DD_i} = (\ell^{T}_{2i+1} - \ell^{T}_{1i+1}) - (\ell^{T}_{2i} - \ell^{T}_{1i}) + [(b_2-b_1)_{i+1} - (b_2-b_1)_i] \qquad (9)$$

The term in the brackets will be extremely small and it is therefore hoped that the final misclosure will be completely free of the orbital model biases. Care should be taken to compute independent double differences (that is, use observations 1-2, 3-4, 5-6, etc. and not 1-2, 2-3, 3-4, etc.). If correlated observations are used then the correlations should be included in the error propagation process or the adjustment results are meaningless. In this case however, the computational burden is such that it makes the problem unsolvable in practice.

2.214 Preliminary results from the 1979 Lageos data.

The laser systems operating during this time period were not particularly well distributed for providing simultaneous tracking of Lageos, and even worse, the ones that had collected any significant amounts of data were all on the continental USA (the five laser-VLBI intercomparison campaign stations). It is not surprising, therefore, that only a few short time intervals (3-5 days) existed in this data set which could be used to test the developed software. The November 27 through November 30,1979, interval was finally selected as the one to be used for the tests. Stations which had simultaneous tracking during this period are : STALAS at GSFC(7063), Haystack (7091), Owens Valley (7114), Goldstone (7115), and Pt. Davis (7086). It is worth noting that although about 21,000 ranges were collected during this period, only 1/7 of them fell in the simultaneous tracking category. Out of these 3000 ranges a data set of about 1000 range-differences was compiled using the technique outlined in Appendix 1, taking into account that the resulting differences should be uncorrelated (assuming that the original ranges are such). The station locations and the simultaneous events on the six Lageos passes are shown in Fig.1 . In Tables 1 and 2, the number of events per station and per baseline respectively are given for each pass. The totals in the bottom line of the first table indicate the number of independent events in each pass, while the columns indicate how many times each station participated in an event. The grand total is the total number of events in the experiment. The numbers in the second table have a similar meaning, except that we are now considering station pairs rather than the stations independently.

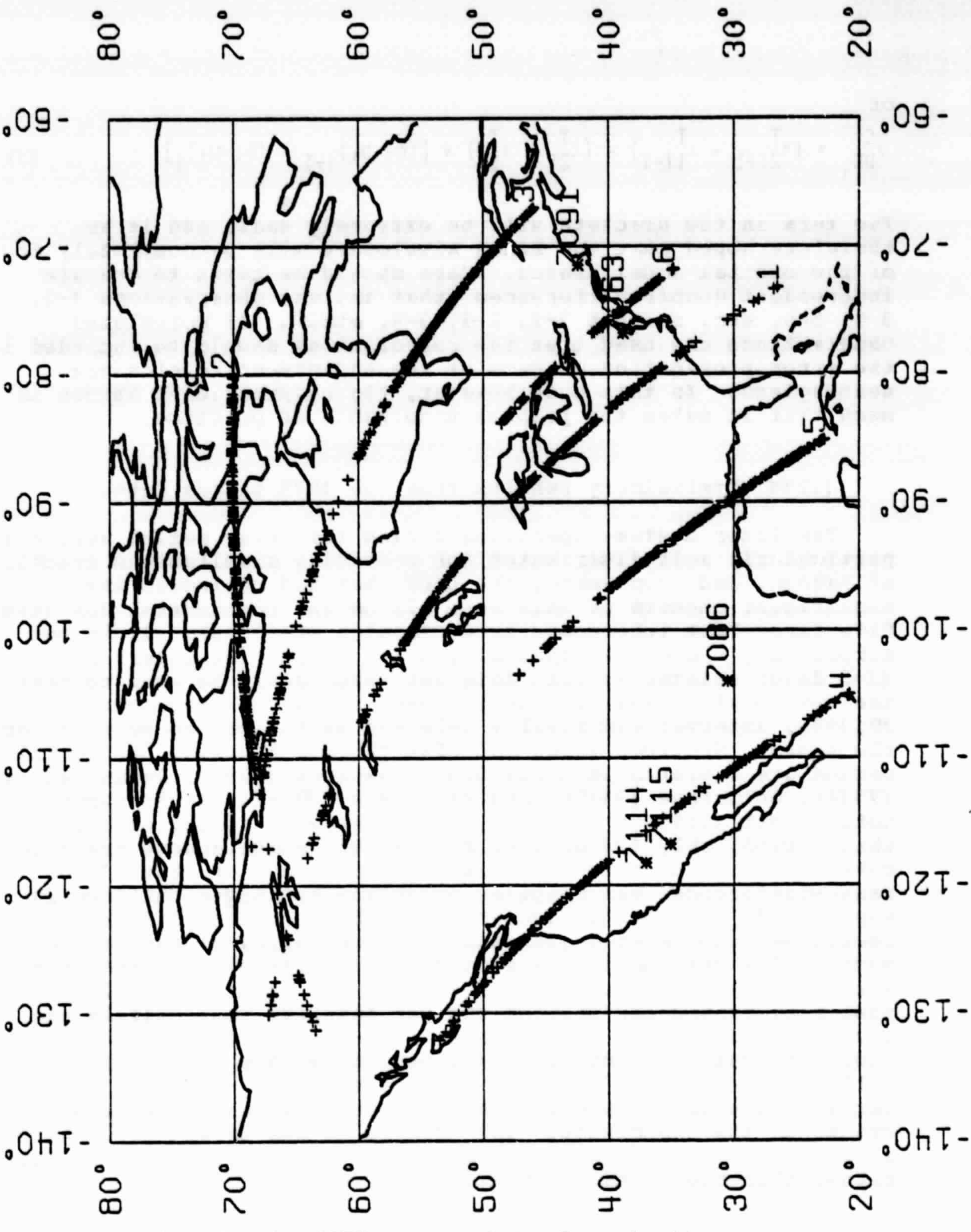


Fig. 1. The 1979 Lageos data for simultaneous range-differencing.

Table 1 Simultaneous Events Distribution by Station

Station	Lageos Pass 1	2	3	4	5	6	Total
7063	206	0	106	14	108	52	488
7086	5	0	0	73	108	60	246
7091	0	155	173	113	111	19	571
7114	201	0	108	0	0	11	320
7115	0	155	173	54	111	0	493
Total	206	155	281	127	219	71	1059

Table 2 Simultaneous Events Distribution by Baseline

Baseline	Lageos Pass 1	2	3	4	5	6	Total
7063-7114	201	0	108	0	0	0	309
7063-7086	5	0	0	14	108	52	179
7115-7091	0	155	173	54	111	0	493
7091-7086	0	0	0	59	0	8	67
7091-7114	0	0	0	0	0	11	11
Total	206	155	281	127	219	71	1059

Examining these tables, and especially the second one, it is obvious that only the first (7063-7114) and the third (7091-7115) baselines have any significant number of observations to produce a meaningful estimate. In fact the two together account for more

than 3/4 of the total number of events. Unfortunately, looking at Fig. 1 it is evident that all of the observed passes are in the same general direction. The two baselines mentioned above are also so nearly situated that the fact that we have data from both is irrelevant; we would have the same amount of information if we had the same number of events from either one only. So due to this poor geometry of our network it is improbable that any biases will be eliminated by simple differencing. In most cases the range from one end of the baseline is several times longer compared to the one from the other end, and in a quite different direction with respect to the satellite groundtrack.

2.215 Results and conclusions.

In light of the above remarks one would therefore expect no astonishing results out of this experiment. As a matter of fact these tests were done to check the developed software rather than the underlying method. Certain conclusions though can be still safely drawn, so that we consider them in future experiments. As far as polar motion is concerned, a well balanced set of passes is very important. Although a pair of orthogonal baselines can provide estimates for both of the components in theory, a worldwide set of such evenly distributed pairs is what we should be planning for. Clustering of station pairs on any particular side of the earth results in highly unstable critical configurations, which introduce unacceptable correlations between the estimated parameters. In this case, for instance, the Z-component of the station positions is extremely weakly determined, being highly correlated with the Y-component, a result of the fact that all stations are at about the same latitude. A comparison of the results obtained from range-differences with those obtained from the same data set but using the range approach instead, showed that the latter is more severely affected by the poor geometry than is the former.

It is hoped that a new set of data, which is now being selected from the MERIT '80 Lageos data, will contain a sufficient number of observations from other areas of the world (e.g., the Pacific Ocean and the Australian stations) which will allow for a more meaningful comparison of the actual estimates to those obtained by other techniques.

References

Van Gelder, B.H.W. (1978) "Estimability and Simple Dynamical Analyses of Range (Range-Rate and Range-Difference) Observations to Artificial Satellites," Dept. of Geodetic Science Rep. 284, Ohio State Univ., Columbus.

2.22 Doppler Experiments

2.221 Geometric solution using ranges derived through simultaneous Doppler observations: Victoriaville data set

Introduction

The National Geodetic Survey (NGS) was invited by Sheltech Ltd., Calgary, Alberta, Canada, and Quebec Lands and Forests to participate in the evaulation of the Doppler data set collected by eight stations that were observing during the period of October 2-5, 1979. These stations were occupied simultaneously using JMR-1 receivers. The stations were spaced within 6 - 30 km of each other. These stations have been tied by conventional survey techniques to the national NAD network. The survey was done under second-order specifications. Stations E43, 404 and 273 were established on existing points.

Doppler Test for Point Positioning.

The above data were processed and reduced by NGS with point-positioning program DOPPLR and the "precise" ephemerides. These results were used to verify relative positioning accuracies obtained by other Doppler reduction programs--multi-station short arc programs GEODOP and SAGA III.

The same data were also processed and reduced properly to be used by the GEODOR relative positioning program through a geometric range adjustment (geometrical solution).

This report focuses only on the data reductions performed to be used by GEODOR, on the results and comparisons with terrestrial network positional information.

Data Processing and Reduction

The Doppler data sets were received from Richard Moreau, Director of Service de la Recherche et du Developpement Technologique. The raw data had been preprocessed by Sheltech using a program similar to JMR's SP-2T version.

The data that were received are:

--one tape containing the Doppler data, Victoriaville project

--meteorological data

--page from GEODOP showing initial values of receiver delays, approximate coordinates and antenna height

--pages 11 and 12 from the Sheltech report

--copy of letter to P. Gagnon giving the final precise coordinates obtained by standard methods, undulations as computed by G. Lachapelle, and (added by hand) antenna heights. The undulations refer to the Clarke 1866, and the datum shifts with respect to 1927 NAD (nominal Canadian values) are:

$$\Delta x = 15 \text{ m}$$
$$\Delta y = -165 \text{ m}$$
$$\Delta z = -175 \text{ m}$$

The problem of positioning with geometric solution requires six simultaneously observing stations. In this data, eight stations at most were simultaneously observing. Fig. 1 is a sketch of the test network.

Derivation of the Ranges

(1) The pass header timing, the mean orbital parameters, and the ephemeral parameters were the main input to a program supplied to us by H. White. The output was the state vectors at two-minute intervals for all the passes. These state vectors refer to an earth-fixed geocentric coordinate system.

Decoding the ephemeral parameters, it turned out that the data (as they were majority voted) have ephemeral parameter information for at most two minutes before lock-on time. In some passes, it was found that in the ephemeral parameter information the time was wrong. These passes were taken out.

(2) Using the remaining passes, the Doppler counts and the corresponding time information was the input to the program "DOPPLR1." This program is a modification of a part of the program JMRDOP-A supplied to us by Larry Hothem. The output was station ID, satellite ε_1 time, duration of the Doppler counts, ε_2 time. The above information were sorted according to satellite and time.

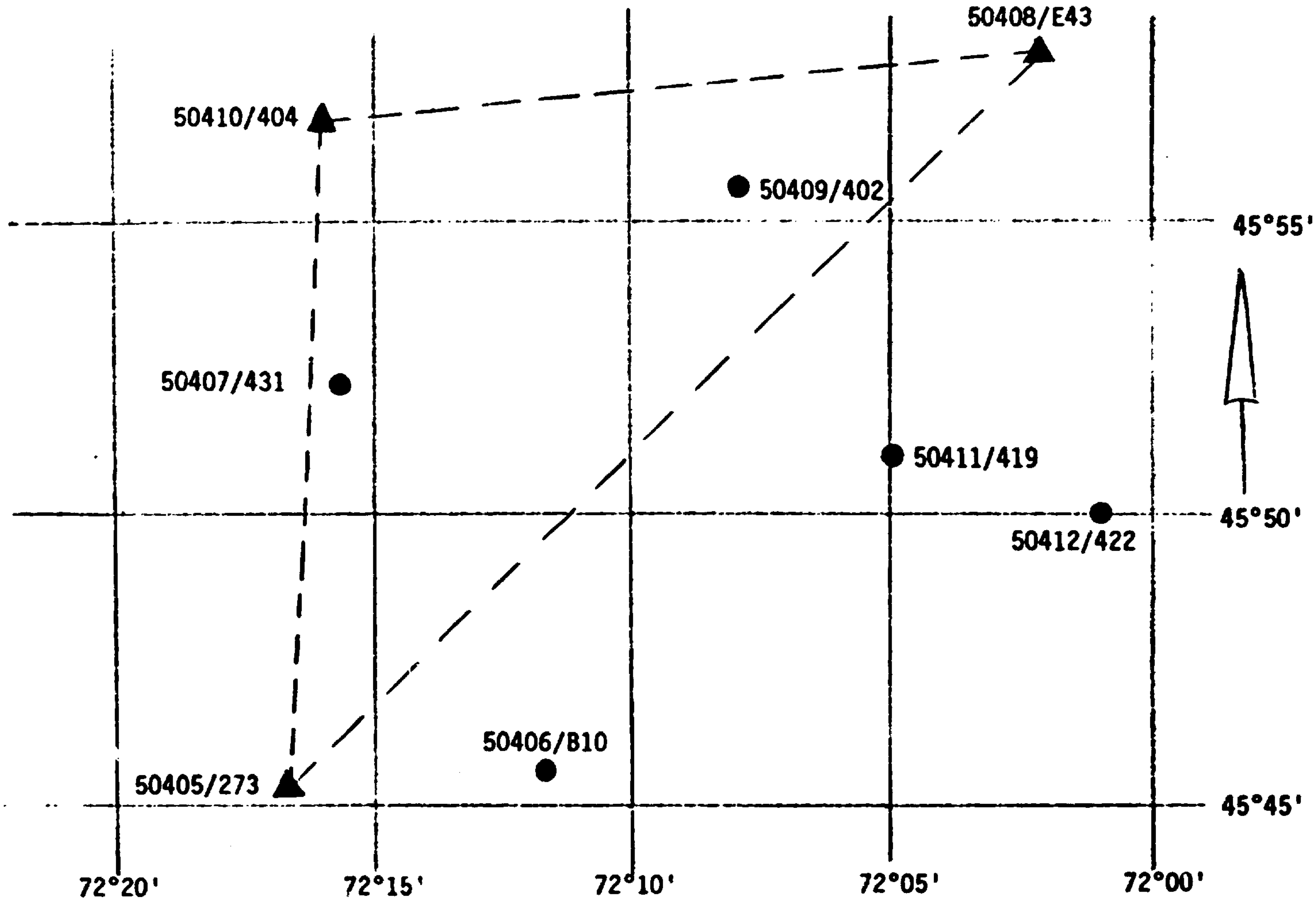


Fig. 1 Quebec Doppler test survey.

Examining the above results, it was found that there were discrepancies in the time corresponding to the duration of the Doppler counts. In order to correct these discrepancies, the following procedure was applied:

(2a) Given the satellite coordinates at two-minute intervals (taken from White's output), the polynomial coefficients were computed for each pass and each coordinate separately. This was done by fitting each position component as a function of t_i to a fifth-order polynomial.

The general equation for X is given by

$$X_i = a_0 + a_1 t_i + a_2 t_i^2 + \dots + \alpha_n t_i^n \tag{1}$$

The same equation was applied for the Y and Z coordinates.

Using the fifth-order polynomial coefficient for each pass and each coordinate (as obtained from step (2a)), the coordinates of the satellite were able to be computed at the epochs t_1, t_2 (see Fig. 2). Knowing the coordinates of the ground stations, the distances S_1 and S_2 were computed. Therefore, it follows that:

$$t_2 = t_1 + \tau_1 + d + \varepsilon_1 + T - \varepsilon_2 - d - \tau_2 \tag{2}$$

$$t_2 - t_1 = \tau_1 + \varepsilon_1 + T - \varepsilon_2 - \tau_2 \tag{3}$$

where

$t_2 - t_1 = 4.601016$ s or $t_2 - t_1 = 4.9746028$

d = receiver electronic delay

The values τ_1, ε_1, T, ε_2, τ_2 were computed using the data. So the computed value

$$a = \tau_1 + \varepsilon_1 + T - \varepsilon_2 - \tau_2$$

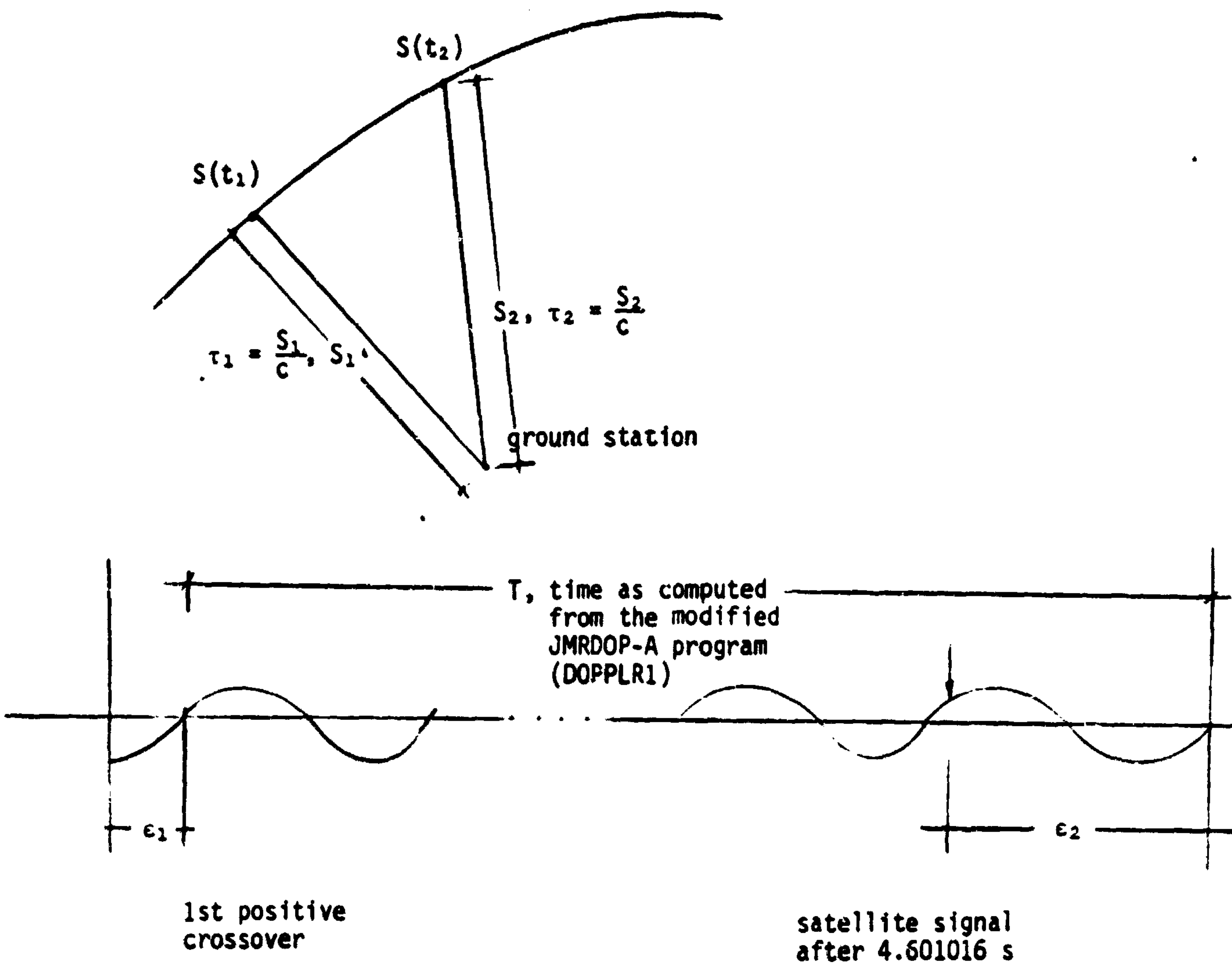
is different from the value $t_2 - t_1$. Therefore, the correction b to be applied to the T-term is given as:

$$b = (t_2 - t_1) - a$$

The following assumptions are made:

(a) No errors in the satellite clock,

(b) No relativistic phenomena,



$S(t_2)$
$S(t_1)$
$S_2,\ \tau_2 = \frac{S_2}{c}$
$\tau_1 = \frac{S_1}{c},\ S_1$
ground station
T, time as computed from the modified JMRDOP-A program (DOPPLR1)
ϵ_1
ϵ_2
1st positive crossover
satellite signal after 4.601016 s

Fig. 2

(c) The only source of errors is the duration of the Doppler counts T as computed from DOPPLR1 (JMRDOP-A modified program).

These assumptions will be elaborated on in a report now in preparation.

(3) Using the above information, a program was written to compute the geometric ranges for each observation for all the passes. The input for this program was (a) station ID, satellite ID, beginning of each observation, Doppler counts, ϵ_1 time, duration of the Doppler counts, ϵ_2 time, correction to be applied to the duration of the Doppler counts; (b) fifth-order polynomial coefficients for each pass and each coordinate of the satellite.

The output was: station ID, satellite ID, beginning of the Doppler counts, Doppler counts, duration of the Doppler counts, correction to the duration of the Doppler counts, X,Y,Z satellite coordinates, and the geometric range.

The input to the program was sorted according to station ID and satellite ID.

(4) The "OVERLAP" program has been used and the common observations have been identified. OVERLAP was fed the output of step (3) above, after sorting it according to satellite ID and the time. The output of OVERLAP was:

(a) pass number, number of co-observing stations, satellite ID,
(b) year-month-day, hour-minute-seconds, modified Julian day for the beginning of each pass,
(c) year-month-day, hour-minute-seconds, modified Julian day for the end of each pass,
(d) ID of co-observing stations,
(e) number of events of the co-observing stations.

(5) A program was written to select the common observations where six or more stations were observing simultaneously. The input to this program was:

(a) the output of (3) above after sorting it according to satellite and the time referred to the beginning of the Doppler counts, and

(b) the output of the fourth step (OVERLAP output).

The output of this program was: station ID, satellite ID, modified Julian day for the beginning of each Doppler count, Doppler counts, duration of the Doppler counts, correction to the duration of the Doppler counts, X,Y,Z coordinates of the satellite, and geometric range.

(6) The meteorological data for each station were sent to us separately as they were recorded during the period of the observations. A program was written to get the meteorological data for each station at the mid-arc epoch of each pass (using linear interpolation). The input of this program was:

(a) the OVERLAP output as it was obtained in the fourth step (taking into consideration only passes which contained six or more co-observed stations),
(b) station ID, time in modified Julian day, pressure in millibars, temperature in degrees Celsius, relative humidity.

The output of this program was:

(a) the OVERLAP output as it was obtained in the fourth step (considering only passes which contained six or more co-observed stations), and
(b) station ID, modified Julian day at the mid-arc epoch of each pass, pressure, temperature, relative humidity referred to the mid-arc epoch of each pass.

(7) A final program was written to obtain the Doppler range differences, the tropospheric refraction correction, and the input files for the GEODOR relative positioning program. The input of this program was:

(a) the output of the sixth step,
(b) the output of the fifth step.

The output of this program was:

(a) satellite ID, modified Julian day (integer), time of the beginning of each pass, time of the end of each pass, number of stations observing in that particular pass, ID of the pass, number of events for the particular pass, maximum number of stations observing this particular pass.

(b) station ID, ID of the pass, α term, b term, time from the beginning of the pass. The above information was referred per pass per station.

(c) time in modified Julian day, X,Y,Z satellite coordinates, number of co-observing stations per event. This information was referred per each event.

(d) time in modified Julian day, geometric derived range, elevation angle of line of sight to satellite, Doppler derived range, and ID of the station. This information was referred per each observation.

The output of the seventh step was obtained by applying the following formulas:

$$r = \Delta r + r_0 + \Delta_{tr}$$

where:

$\Delta r = \lambda_0 \, [N_i - (f'_{00} - f_{00})\tau_i]$

$\lambda_0 = c/f_{00}$ = wavelength of adopted frequency of satellite oscillator

c = the speed of light (299792458. m/s)

f'_{00} = adopted value of local reference frequency (400 MHz)

f_{00} = adopted value of transmitted frequency by the satellite (399.968 MHz)

τ_i = time interval between two observations

N_i = Doppler counts corresponding to τ_i time

$r_0 = \sqrt{(X_S-X_G)^2 + (Y_S-Y_G)^2 + (Z_S-Z_G)^2}$ = initial range obtained through the initial state vectors geometrically and therefore biased

Δ_{tr} = tropospheric refraction correction = $(n_0-1)H_0/\sin E$

$n_0 = 1 + 10^{-6}\,[N_d + N_w]$ in which N_d and N_w denote the dry and wet contributions to the total refractive index

$N_d = 77.6\ P_0/T_0$

$N_w = 3.73 \times 10^5 \dfrac{e_0}{T_0^2}$

where P_0 = atmospheric pressure (millibars)

T_0 = temperature (degrees Kelvin)

e_0 = water vapor pressure =
$= 6.11 \times R \times 10^{7.5(T_0-273.3)/(T_0-35.8)}$

R = relative humidity (percentage)

H_0 = scale height = 29.2 (T_0-30)

E = elevation angle of line of sight to satellite, therefore changing for each observation

(8) Using the output of the seventh step the GEODOR relative positioning program was used. This program was based on the geometric range adjustment. The mathematical model used for the range adjustment is the following:

$$\bar{r} = [(X_S-X_{G_i})^2 + (Y_S-Y_{G_i})^2 + (Z_S-Z_{G_i})^2]^{\frac{1}{2}} + a_i + b_i\, t_i$$

where

X_S, Y_S, Z_S	are the earth-fixed satellite coordinates
X_{G_i}, Y_{G_i}, Z_{G_i}	are earth-fixed station coordinates
a_i	is a bias for each pass and station in the computation of the initial range. This term can take care of other constant biases such as satellite oscillator offset and receiver oscillator offset
b_i	= time dependent bias
t_i	= time from the beginning of each pass

The "GEODOR" program was run

(a) with a minimum constraint solution. The output showed that the reduced normal equation matrix was singular.

(b) fixing X, Y, Z for the three stations 404, 273, E43. These three stations were established on existing points. The output showed again that the reduced normal equation matrix was singular.

(c) fixing again the X, Y, Z for the above stations and the initial and final range to somehow stabilize the orbital arc. The output showed again that the reduced normal equation matrix was singular.

The problem seems to be the geometrical configuration. Simulated data will be used to verify this guess. The procedure for the range adjustment is based on first-order partitioning regression, and it was an interative procedure described OSU Dept. of Geodetic Science Rep. 199.

References

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McLuskey, D. (1974) "Position Fixing by Doppler Methods," technical paper submitted in partial fulfillment for requirements for MS degree, Dept. of Geodetic Science, Ohio State Univ., Columbus.

Mueller, I.I., M. Kumar, J.P. Reilly, N. Saxena, and T. Soler (1973) "Global Satellite Triangulation and Trilateration for the National Geodetic Satellite Program (Solutions WN12, 14 and 16)," Ohio State Univ. Dept. of Geodetic Science Rep. 199, Columbus.

Mueller, I.I. (1980) "Course material for GS 777 - Satellite Geodesy."

2.222 Geometric solution using ranges derived through simultaneous Doppler observations: EDOC-2 data set.

Since the progress reported on in the last Semiannual Report, work on this project has continued and will be reported on in a report to be issued in the near future.

2.223 Doppler Intercomparison Experiment

Work has been completed on converting the Canadian Geodetic Survey (CGS) GEODOP programs for operation here at OSU. As described in the last semiannual report, this system of programs, which was written mostly by Mr. Jan Kouba of the CGS, was coded in CDC Fortran IV. It has been converted here to operate using an IBM Fortran compiler, specifically the IBM H-Extended Enhanced, or Q compiler (with optimization level 3 and AUTODBL(DBLPAD) options in effect).

The GEODOP PROGRAM SYSTEM

The purpose of this system is to process Doppler observations, taken with several possible types of instruments, of the Navy Navigation Satellite System (NNSS). The names of the specific programs in the system and their overall functions follow:

1. PREDOP - Preprocesses and edits majority voted data from JMR, CMA-722, CMA-751, and raw data from MX-1502 receivers.

2. NWLFIT - Creates a (binary) file of curve-fitted Chebyshev coefficients from Naval Weapons Laboratory (NWL) precise satellite ephemeris.

3. MERGE - Merges (up to 15) single stations into one multi-station file, or will merge one or more station files with NWL fitted precise ephemeris.

4. PREPAR - Preprocesses Geoceiver or TRANET data, and merges it with either broadcast or precise satellite ephemeris provided by PREDOP or NWLFIT respectively.

5. PRERED - Lists a PREDOP, MERGE, or PREPAR created binary file.

6. NWLDUM - Lists a NWLFIT created binary file.

7. GEODOP - Does a pass by pass sequential adjustment of the preprocessed data for up to 15 stations, and provides a solution of station positions (X, Y, Z, ϕ, λ, h), receiver information, orbital and refraction biases, along with appropriate variance-covariance estimates.

Each of these programs has been converted to operate on our system. Considerable testing has been performed to insure that the IBM version gives results which are identical to the CDC

version (with the implicit assumption that the CDC version gives the correct results). Currently some portions of the system, although converted, remain untested, specifically in cases where test data is unavailable and where data of such type will not be used here (i.e., PREPAR and portions of PREDOP have not been tested). The system is completely tested for JMR, CMA-751 (format III) and MX-1502 data.

Description of the Conversion to IBM Fortran

The conversion itself proceeded as follows: An initial copy of the system (designated GEODOP IV) was provided by J. Kouba in December, 1980. The majority of the conversion to IBM Fortran was complete by March, 1981, but several differences appeared between the IBM and CDC version results. Mr. Kouba was extremely helpful here in that he made runs which allowed detailed checking of the GEODOP program itself. It was found that a few minor logical errors in the original program were basically at fault, as the IBM compiler interpreted a few program segments differently. Also, it was finally realized that the CDC version sent here was not identical to the version being used by Mr. Kouba. When a copy was sent back to him, his runs gave identical results for the test data set of OSU CMA-751 data.

In July, 1981, Mr. Kouba sent his revised version of the GEODOP system, designated GEODOP V, which contained several corrections to the GEODOP system, most notably in the ionospheric refraction correction, the partial equations, and other corrections that were noted here during the conversion. Several options had also been added including a gravity model, a receiver timing adjustment in PREDOP, and more importantly an option to edit out non-coobserved ("30 second") observations in GEODOP for multi-station solutions. The importance of the corrections and the usefulness of the additional options led us to update our IBM version to the GEODOP V level. This updating was completed by late August, including testing with two standard data sets (the OSU CMA-751 data, and CGS JMR-1 data) and our MX-1502 data.

In September, a few further minor changes were received from Mr. Kouba, which dealt mostly with printer formatting changes, and the allowance of a higher degree gravity model in PREDOP. These changes have not yet been included in the IBM version but probably will in the near future. Additionaly, a program written here called PLTGEO is now being tested, which will plot the results of the pass by pass GEODOP adjustment on an electrostatic (Versatec) plotter.

Final Plans for the Program System

Once the September program changes have been implemented, along with any other changes found necessary during the processing described below, final documentation will be written explaining the differences in operation of the IBM version as compared to the CDC version. Most of the changes in input have already been documented and a set of example runs have been created to allow testing and easier use of the programs. Documentation will also be written for the PLTGEO program. The IBM version of the GEODOP program will be made available to Mr. Kouba along with the above mentioned documentation. With Mr. Kouba's permission, a nearly final copy has already been supplied to the Defense Mapping Agency through Dr. M. Kumar.

Data Processing

Since the conversion of the GEODOP System is now essentially complete, processing of the data obtained during our intercomparison test in October-November, 1979, has begun. The comparison of the three types of instruments, the JMR-1A, the CMA-751, and the MX-1502 will be based on the answers to the following questions and planned GEODOP runs:

(1) How long will it take to reach a specified accuracy in position in terms of time and/or satellite passes? To answer this, all of the data for each instrument will be processed, primarily to determine how the final absolute position converges for each instrument. Also, when observing over the same time period, what is the final precision (variance) of the absolute position which is obtained (with GEODOP)? The results here will take into account that each of the receivers occupied a total of four stations, and assure there was no bias due to antenna positions.

(2) The above questions can also be posed with the condition that only observations made simultaneously by all the instruments (an "observation" implying a "30 second" Doppler count) should be processed. This will eliminate any bias caused by interference or loss of signal at one receiver, such as due to local interference, the antenna or pre-amplifier design, algorithm used to find and track a satellite, etc. This will allow a more direct comparison of the receivers' oscillators and electronics. This type of run can be made using one of the (new) options of GEODOP itself.

(3) Is there any dependence of the above results on the ephemeris type? Identical runs to the above will be made using the precise ephemeris (for NNSS satellites 14 and 19 only).

(4) How stable are the receiver oscillators? The results of the above runs can be examined to determine the frequency drift, and precision of the frequency offset.

(5) Do the receivers pick up the same number of and quality of satellite passes? The number of passes (and/or observations) tracked, accepted during majority voting, accepted by PREDOP, and accepted by GEODOP will be compared. This should indicate which receivers have a better tracking algorithm and/or better antennas.

(6) How well do the receivers recover the timing information from the satellite? It may be possible to answer this question with the results of the (new) timing adjustment of PREDOP. However, the way in which the JMR and MX-1502 record lock-on times of satellite passes, and the numerous manual resettings of our receiver clocks may not allow this.

(7) How do the final absolute positions of the above runs compare with the known position(s) of the stations? The computed positions can be compared with the astronomic and TRANET determined positions of the stations (after making the appropriate geodetic corrections).

(8) How do the relative positions compare? Do the receivers have a constant bias from the correct absolute position or from each other? Do the positions change with time? A comparison of the results from the above runs should answer this. Additionally, a grand solution of all data and four stations could be made, and the differences between it and the point positioning results noted.

(9) Are the results dependent on the tropospheric or ionospheric refraction model, or the cutoff angle of observations? Several runs with different options and the same data set could be made to answer this.

Of course, as each of these runs are being made, and the above questions answered, modifications will be made in the planning of the runs to obtain the most useful results. It is hoped that the runs (and therefore the intercomparison) will be completed in the near future, and some information obtained on the accuracies obtainable with each instrument type.

3. PERSONNEL

Ivan I. Mueller, Project Supervisor, part time

Brent Archinal, Graduate Research Associate, part time

Yehuda Bock, Graduate Research Associate, part time

George Dedes, Graduate Research Associate, part time

Carole Feole, Student Clerical Assistant, part time through 4/5/81

Despina E. Pavlis, Graduate Research Associate, part time through 6/30/81

Erricos C. Pavlis, Graduate Research Associate, part time

Baldev Singh Rajal, Graduate Research Associate, supported by Department of Geodetic Science, part time through 6/15/81

Rudi Schneeberger, Graduate Research Associate, part time from 6/16 through 8/9/81

Irene B. Tesfai, Secretary, part time

Zhu Sheng-Yuan, Visiting Scholar, without compensation

4. TRAVEL

Y Bock, E.C. Pavlis and Y.S. Zhu
Baltimore, Maryland — May 27-29, 1981
To attend two days of the AGU Annual Spring Meeting.

Ivan I. Mueller
Munich — Aug. 31 - Sept. 5, 1981
To attend IAG Symposium on Geodetic Networks and Computations and to present an invited paper on OSU investigations related to geodetic uses of GPS. To chair a session of the Commission on International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG) as its president. A trip report is presented in Appendix 2.

Erricos C. Pavlis
Greenbelt, Maryland — Aug. 31 - Sept. 2, 1981
To attend Fourth Meeting of the Lageos Working Group at Goddard Space Flight Center. Appendix 1 contains the presentation made.

Ivan I. Mueller
Como, Italy — Sept. 7-9, 1981
To attend the VIII Hotine Symposium on Mathematical Geodesy. A trip report is presented in Appendix 3.

5. REPORTS PUBLISHED TO DATE

OSU Department of Geodetic Science Reports published under Grant No. NSG 5265:

262 The Observability of the Celestial Pole and Its Nutations
by Alfred Leick
June, 1978

263 Earth Orientation from Lunar Laser Range-Differencing
by Alfred Leick
June, 1978

284 Estimability and Simple Dynamical Analyses of Range (Range-Rate and Range-Difference) Observations to Artificial Satellites
by Boudewijn H.W. van Gelder
December, 1978

289 Investigations on the Hierarchy of Reference Frames in Geodesy and Geodynamics
by Erik W. Grafarend, Ivan I. Mueller, Haim B. Papo, Burghard Richter
August, 1979

290 Error Analysis for a Spaceborne Laser Ranging System
by Erricos C. Pavlis
September, 1979

298 A VLBI Variance-Covariance Analysis Interactive Computer Program
by Yehuda Bock
May, 1980

299 Geodetic Positioning Using a Global Positioning System of Satellites
by Patrick J. Fell
June, 1980

302 Reference Coordinate Systems for Earth Dynamics: A Preview
by Ivan I. Mueller
August, 1980

320 Prediction of Earth Rotation and Polar Motion
by Sheng-Yuan Zhu
September, 1981 (in press)

The following papers were presented at various professional meetings and/or published:

"Concept for Reference Frames in Geodesy and Geodynamics"
AGU Spring Meeting, Miami Beach, Florida, April 17-21, 1978
IAU Symposium No. 82, Cadiz, Spain, May 8-12, 1978
7th Symposium on Mathematical Geodesy, Assisi, Italy, June 8-10, 1978
"Concepts for Reference Frames in Geodesy and Geodynamics: The Reference Directions," Bulletin Geodesique, 53 (1979), No. 3, pp. 195-213.

"What Have We Learned from Satellite Geodesy?
2nd International Symposium on Use of Artificial Satellites for Geodesy and Geodynamics, Lagonissi, Greece, May 30 - June 3, 1978

"Parameter Estimation from VLBI and Laser Ranging"
IAG Special Study Group 4.45 Meeting on Structure of the Gravity Field
Lagonissi, Greece, June 5-6, 1978

"Estimable Parameters from Spaceborne Laser Ranging"
SGRS Workshop, Austin, Texas, July 18-23, 1978

"Defining the Celestial Pole," manuscripta geodaetica, 4 (1979), No. 2 pp. 149-183.

"Three-Dimensional Geodetic Techniques"
Technology Exchange Week, Inter-American Geodetic Survey
Fort Clayton, Canal Zone, May 14-19, 1979
published in Spanish as "Tecnicas Geodesicas Tridimensionales," Memoria de la Semana de Intercambio Tecnologico, Panama, Rep. de Panama, pp. 400-426.

"On the VLBI-Satellite Laser Ranging 'Iron Triangle' Intercomparison Experiment," Meeting on Radio Interferometry Techniques for Geodesy, Massachusetts Institute of Technology, Cambridge, June 19-21, 1979

"Space Geodesy for Geodynamics, A Research Plan for the Next Decade"
Sonderforschungsbereich - Satellitengeodäsie - SFB 78
Colloquium in Viechtach, FRG, October 23-24, 1979

"Concept of Reference Frames for Geodesy and Geophysics"
seminar given at University of Stuttgart, West Germany, June 19, 1980

"Space Geodesy and Geodynamics,"
seminar given at University of Stuttgart, West Germany, June 26, 1980

"Geodetic Applications of the Global Positioning System of Satellites and Radio Interferometry," seminar given at University of Stuttgart, West Germany, July 3, 1980

"Reference Coordinate Systems for Earth Dynamics: A Preview,"
Proc. of IAU Colloquium 56 on Reference Coordinate Systems for Earth Dynamics," September 8-12, 1980, Warsaw, Poland, E.M. Gaposchkin and B. Kołaczek, eds., D. Reidel. Presented at AGU, San Francisco, December, 1980.

"Comments on Conventional Terrestrial and Quasi-inertial Reference Systems," with J. Kovalevsky, Proc. of IAU Colloquium 56 on Reference Coordinate Systems for Earth Dynamics, September 8-12, 1980, Warsaw, Poland, E.M. Gaposchkin and B. Kołaczek, eds., D. Reidel.

"Precise Positioning with GPS"
seminar given at Deutsche Geodätische Forschungsinstitut, Munich, West Germany, September 18, 1980

"Tecnicas Geodesicas Tridimensionales"
(translated from English by IAGS), ASIA Journal (Asociacion Salvadorena de Ingenieros y Arquitectos) San Salvador, No. 61, Oct. 80, pp. 40-51; cont'd in No. 62, Dec. 80, pp. 31-39.

"Space Geodetic Techniques and Geodynamics"
Proc. 1st International Symposium on Crustal Movements in Africa
Addis Ababa, Ethiopia, May 5-16, 1981

"Comparison of Polar Motion Data from the 1980 Project MERIT Short Campaign"
Proc. of IAU Colloquium 63 on "High Precision Earth Rotation and Earth-Moon Dynamics: Lunar Distances and Related Observations," May 22-27, 1981, Grasse France, D. Reidel (I.I. Mueller, B.S. Rajal and S.Y. Zhu)

"Geodesy and the Global Positioning System"
Proc. of IAG Symposium on Geodetic Networks and Computations, Aug. 31-Sept. 5, 1981, Munich (I.I. Mueller and B. Archinal)

4th Lageos Working Group Meeting, September 1-2, 1981
NASA Goddard Space Flight Center, Greenbelt, Maryland

UTILIZATION OF LAGEOS LASER RANGE DIFFERENCES IN GEODYNAMICS

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Introduction

The objectives of this study are the development and implementation of the technique of range differencing with Lageos ranges in order to obtain more accurate estimates of baseline lengths and polar motion variations. It is expected, and the simulations done to date confirm this, that by means of differencing quasi-simultaneous range observations a great deal of orbital biases can be eliminated resulting in an estimate which is virtually bias free. In the past, attempts were made to use real data in order to assert the conclusions made on the basis of the simulations. Due to the poor geometry and distribution of the data, these attempts fell short of providing any conclusive results. It was realized, however, that even with the best possible geometry and distribution of the observations, certain physical phenomena would have to be included in the model. We are currently investigating these effects on the recovered parameters.

Data Preprocessing

Since it is quite improbable, if not impossible, to obtain exactly simultaneous laser observations from two ground stations to a satellite, the required observations must be interpolated from available commonly tracked passes. Modern lasers have high repetition rates and given fair weather conditions and accurate predictions, a sequence of ranges at a rate of about 1 pps can easily be achieved. Since an average Lageos pass lasts about half an hour, this implies a large amount of data. The high altitude of the target makes it possible to track it

from several stations simultaneously, even if the stations' separation is of continental extent. The current procedure to obtain the quasi-simultaneous ranges [Fig. 1] from data sets such as described above is to determine the "overlap" observations for the station pairs involved, isolate these observations and determine which of the two stations in each pair has a denser data distribution. Once this is determined, the data of the station with the most observations are fed into a cubic-spline interpolator and ranges are obtained for each of the data points in the alternate station's record. These ranges then are differenced to produce the simultaneous range-difference data. The data used in this procedure have already been corrected for systematic errors. Figs. 2 and 3 depict the data record for two passes of Lageos. The bars indicate the epochs when the actual observations occurred and the curve which joins their centers is the spline fit to these data. The stations marked with (*) are the ones for which we used the original observations in the formation of the range differences.

Sensitivity Analysis

Our initial sensitivity study for the proposed method indicated that the key factors in the success of the method (for polar motion variations determination) is the geometry of the network, length of the baselines between co-observing stations and their absolute location. Examining the structure of the sensitivity matrix for these parameters we could deduce a number of important items. With proper choice of the station pairs a nearly orthogonal system can be achieved. This means that each pair will be primarily sensitive to one of the components of the variation. This is illustrated in Fig. 4a & b and Fig. 5a & b where the matrix values have been plotted for the ξ and η components respectively. The top plots correspond to a 1000 km long north-south baseline, while the ones at the bottom to a baseline of the same length but in an east-west direction. The same conclusion can be reached looking at Fig. 6a & b and Fig. 7a & b which depict the situation for baselines 4000 km long. By comparing the two sets of plots it is evident that there is a linear relationship between the baseline length and the sensitivity of the system in the variations of the pole. The baselines for these graphs are all situated near the 0° longitude; similar graphs for these baselines have been examined for longitude 90° W. The conclusions for that case are the same as the previous ones if the ξ and η components are reversed (see Fig. 8).

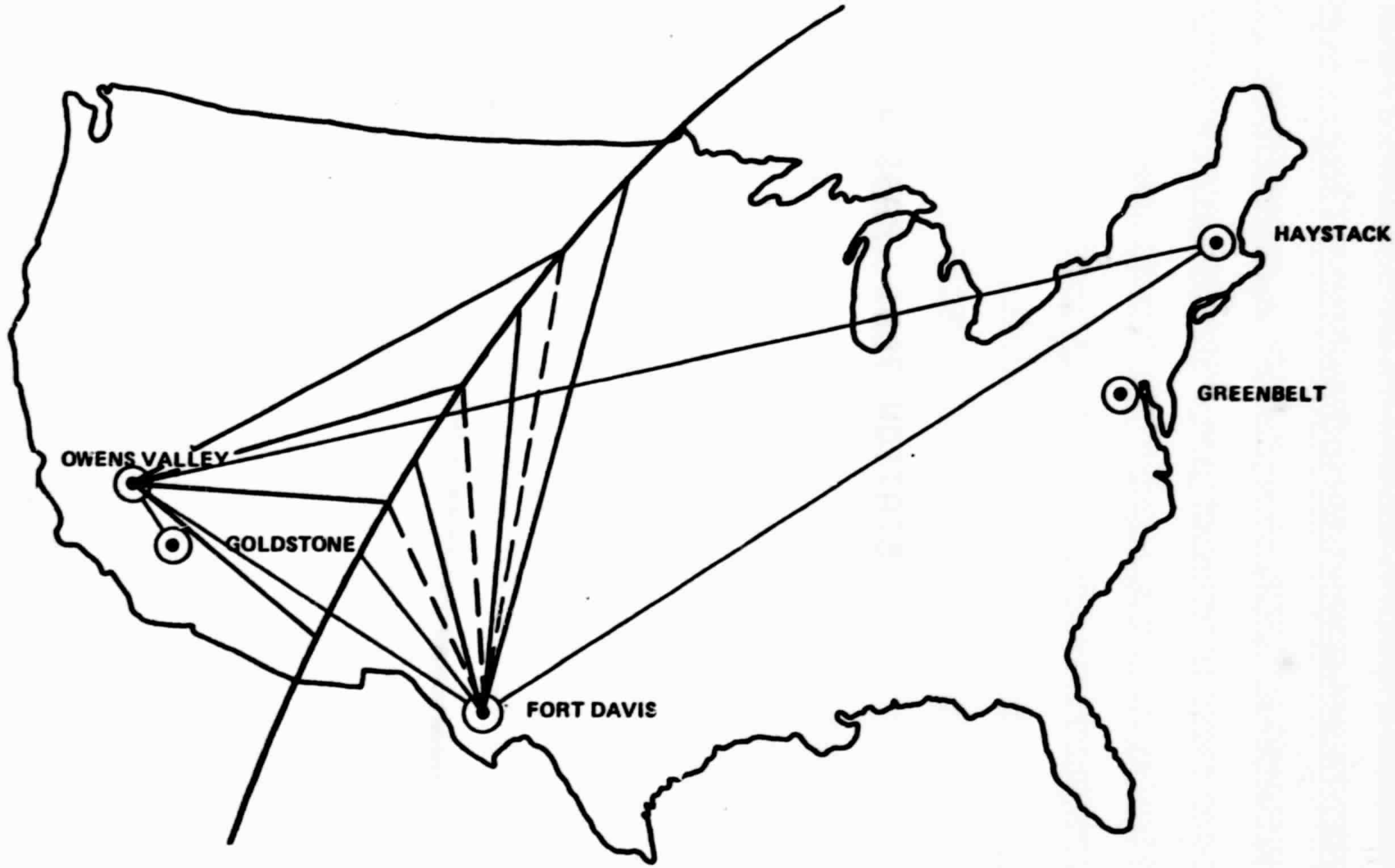


Fig. 1 Simultaneous laser range-differences
(The dashed lines are the interpolated ranges.)

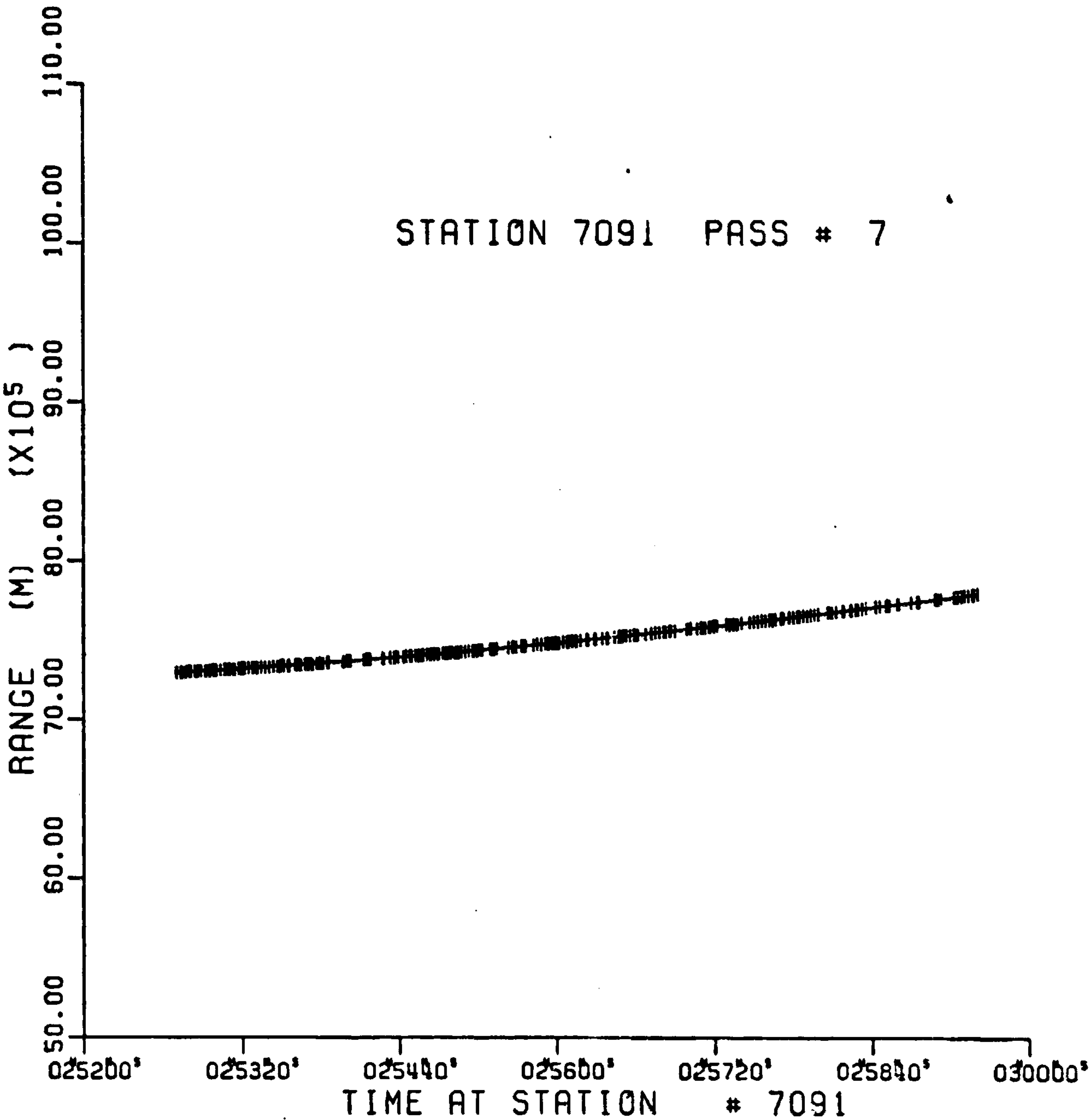
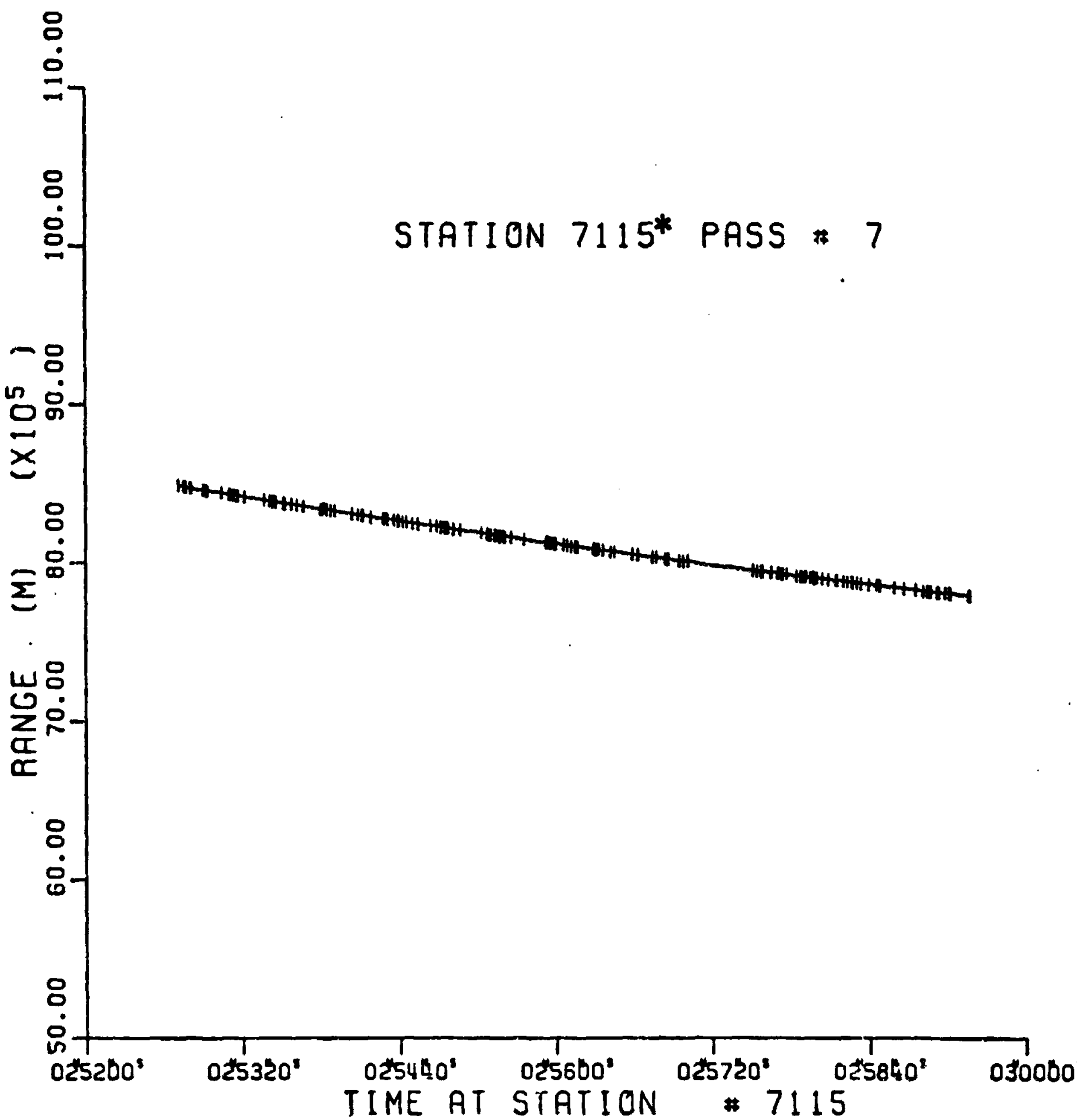

STATION 7091 PASS # 7
RANGE (M) (X10^5)
50.00
60.00
70.00
80.00
90.00
100.00
110.00
$02^h52^m00^s$
$02^h53^m20^s$
$02^h54^m40^s$
$02^h56^m00^s$
$02^h57^m20^s$
$02^h58^m40^s$
$03^h00^m00^s$
TIME AT STATION # 7091

Fig. 2


STATION 7115* PASS # 7
RANGE (M) (X10^5)
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100.00
90.00
80.00
70.00
60.00
50.00
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02h53m20s
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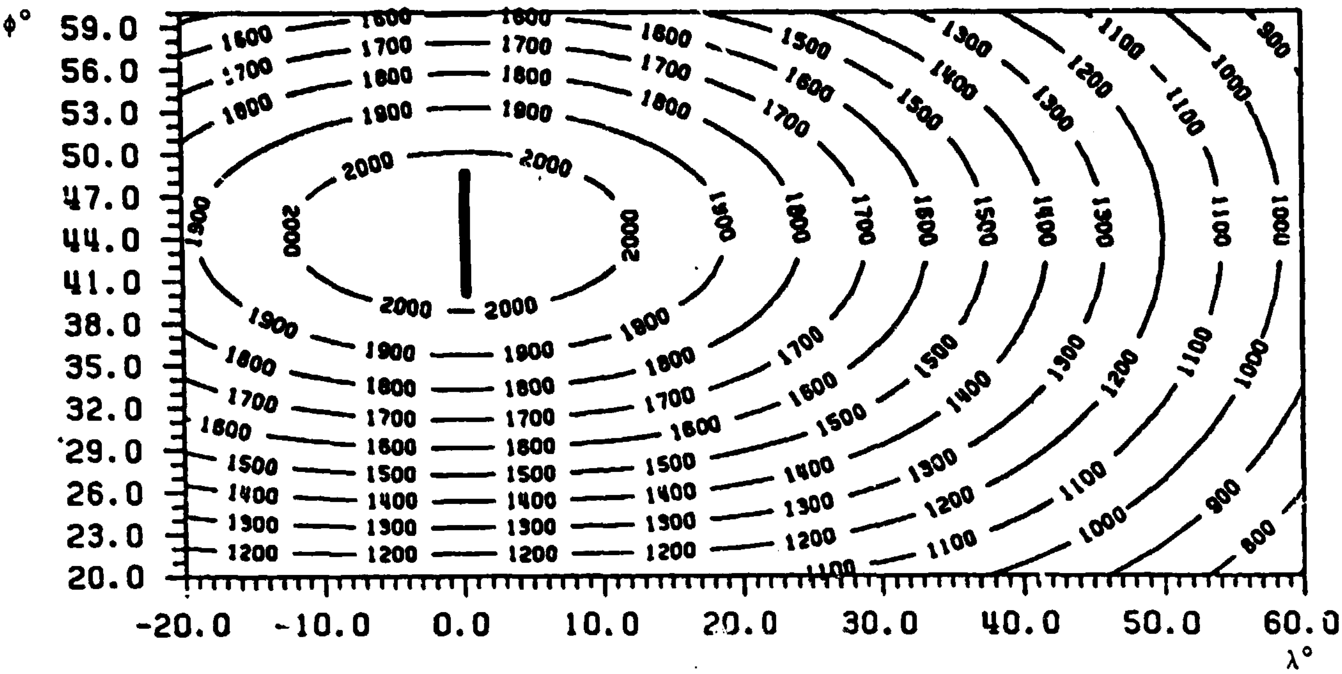
02h56m00s
02h57m20s
02h58m40s
03h00m00s
TIME AT STATION # 7115

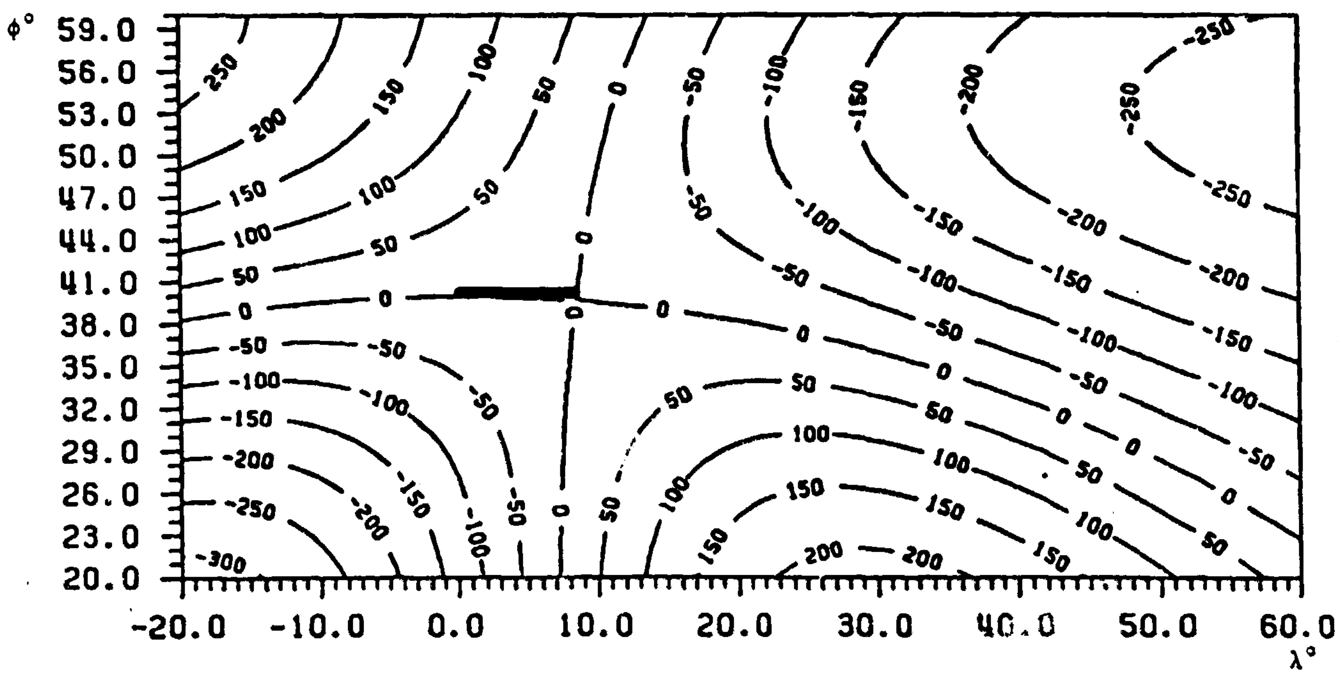
Fig. 3

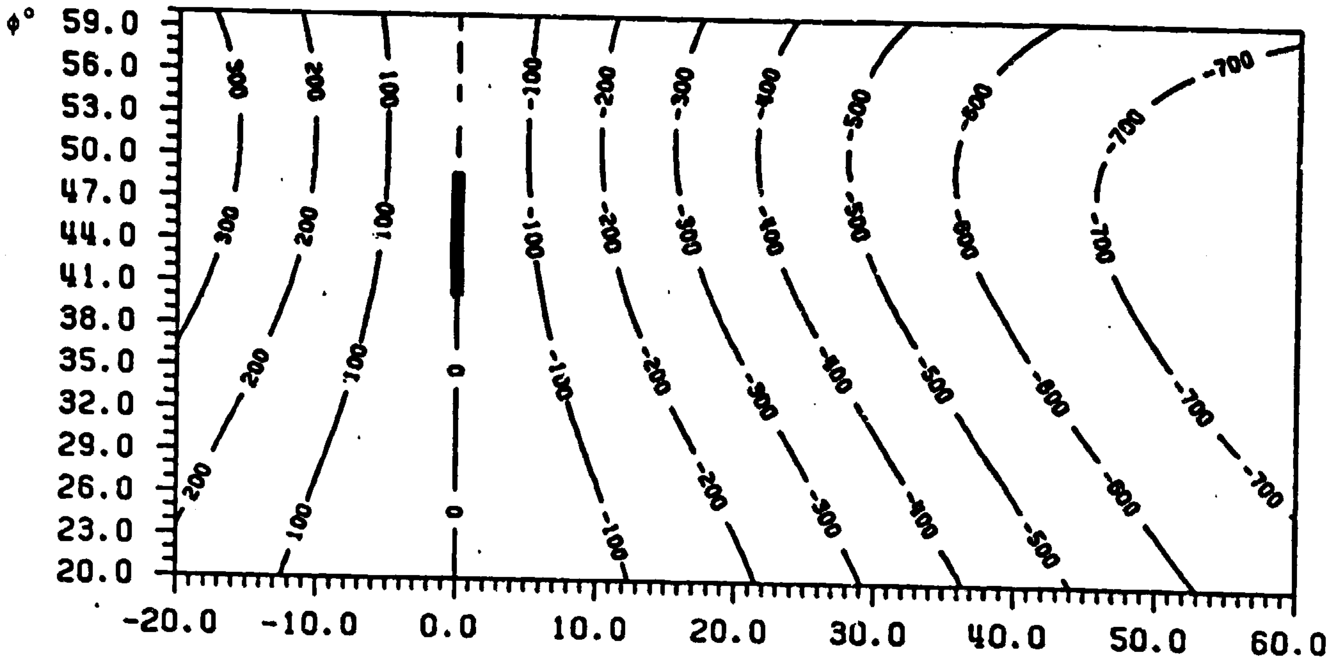


a. North-South baseline.

Fig. 4 Sensitivity matrix plot for the ξ component.
(Baseline length -1000 km)

b. East-West baseline.

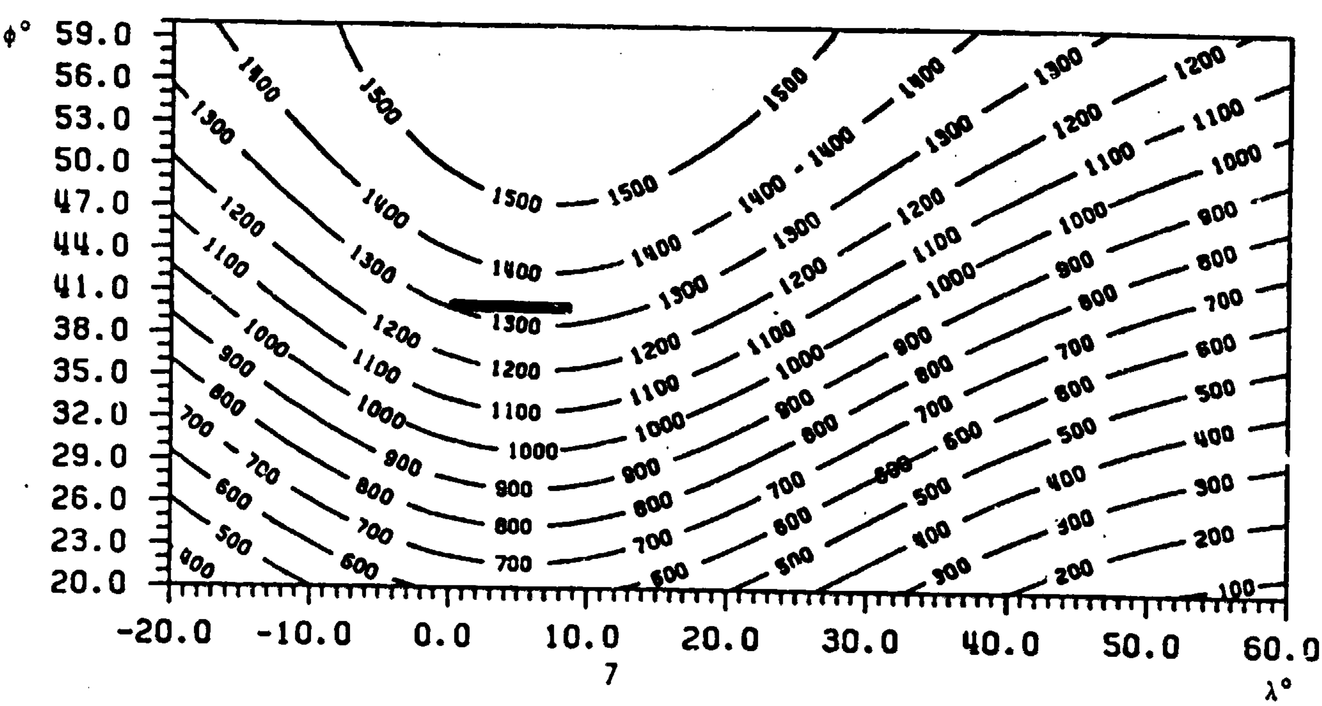


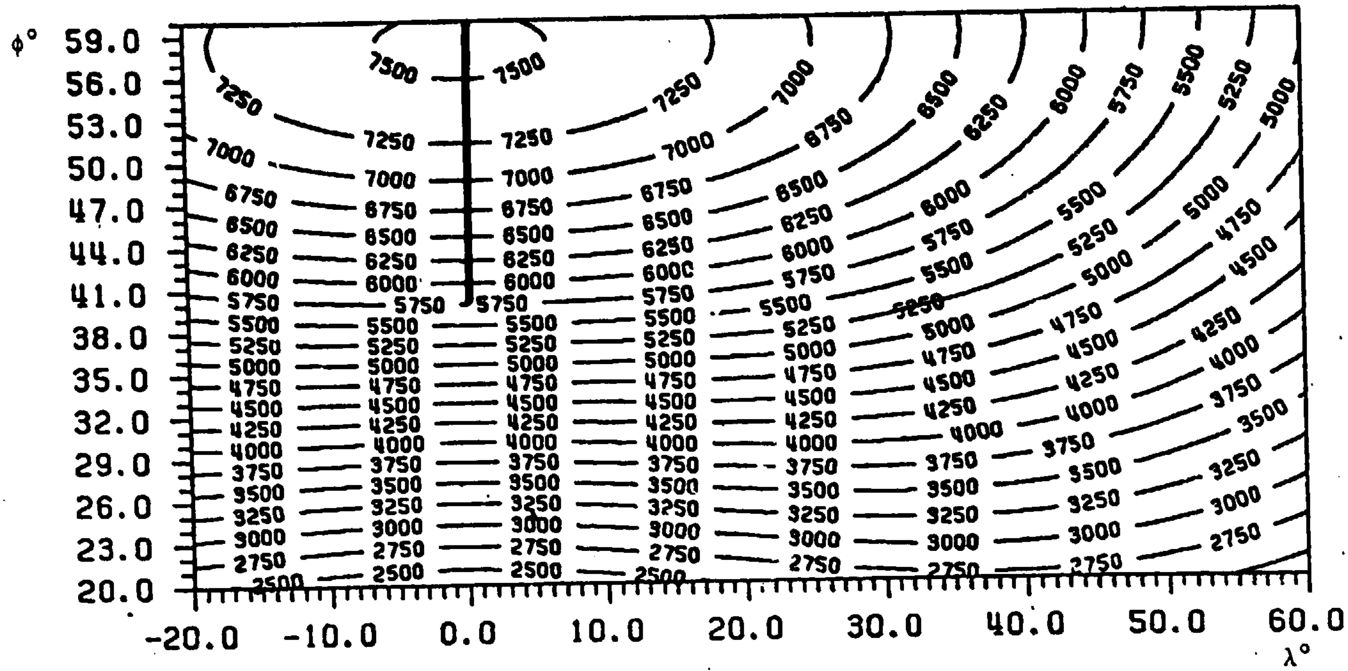


a. North-South baseline.

Fig. 5 Sensitivity matrix plot for the η component.
(Baseline length ~1000 km)

b. East-West baseline.

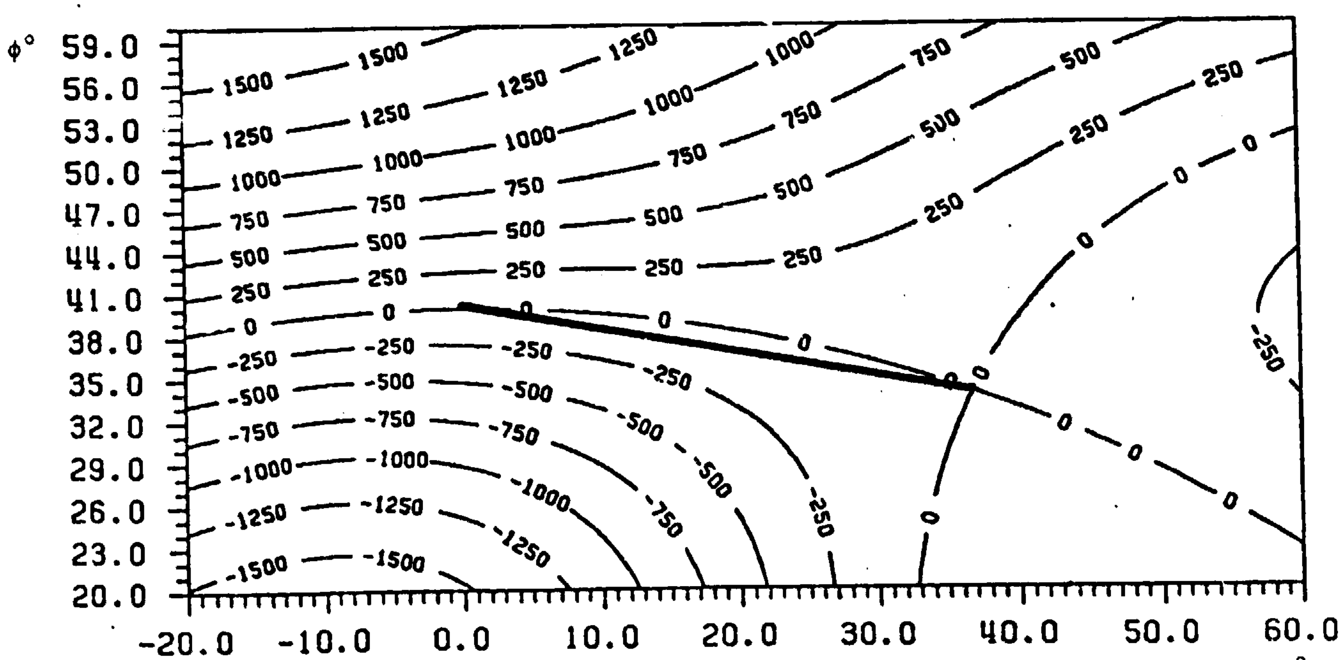


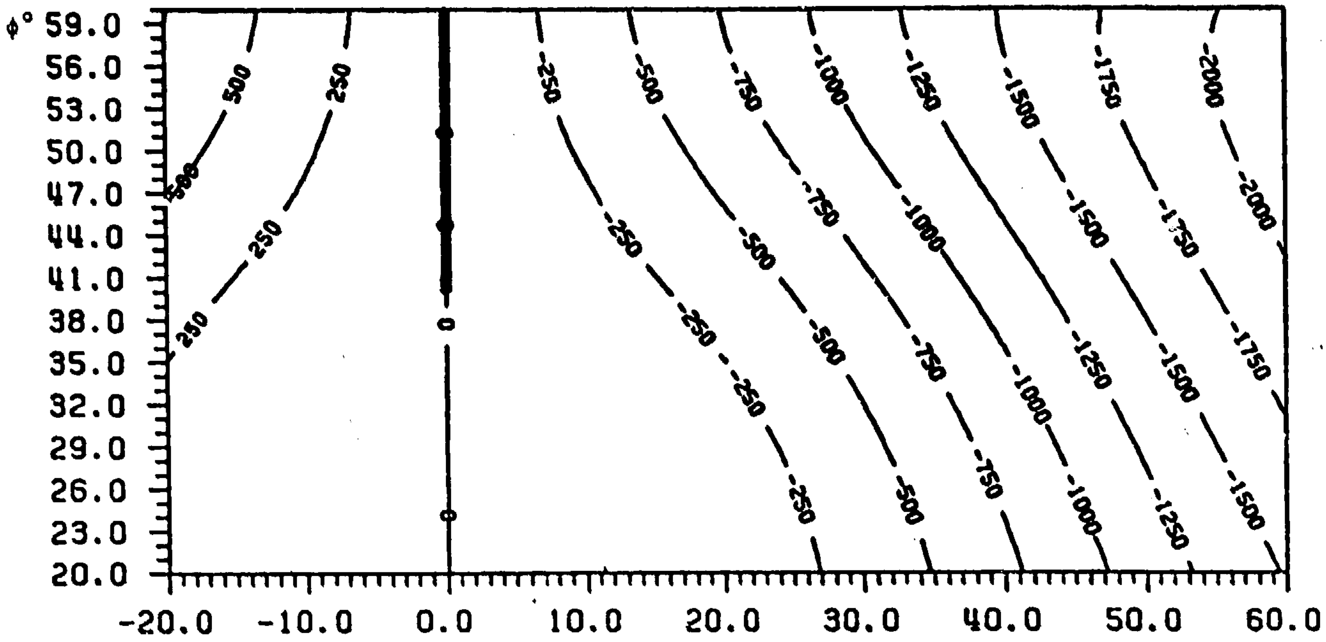


a. North-South baseline.

Fig. 6 Sensitivity matrix plot for the ξ component. (Baseline length ~4000 km)

b. East-West baseline.





a. North-South baseline.

Fig. 7 Sensitivity matrix plot for the n component.
(Baseline length ~4000 km)

b. East-West baseline.

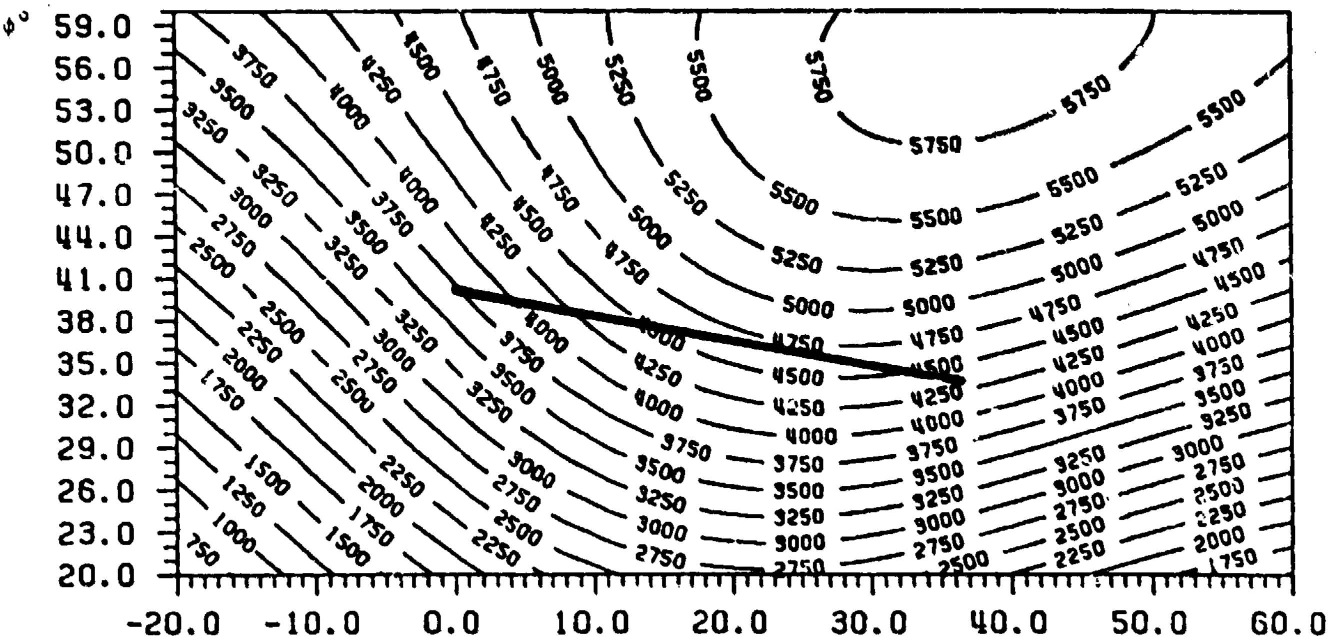
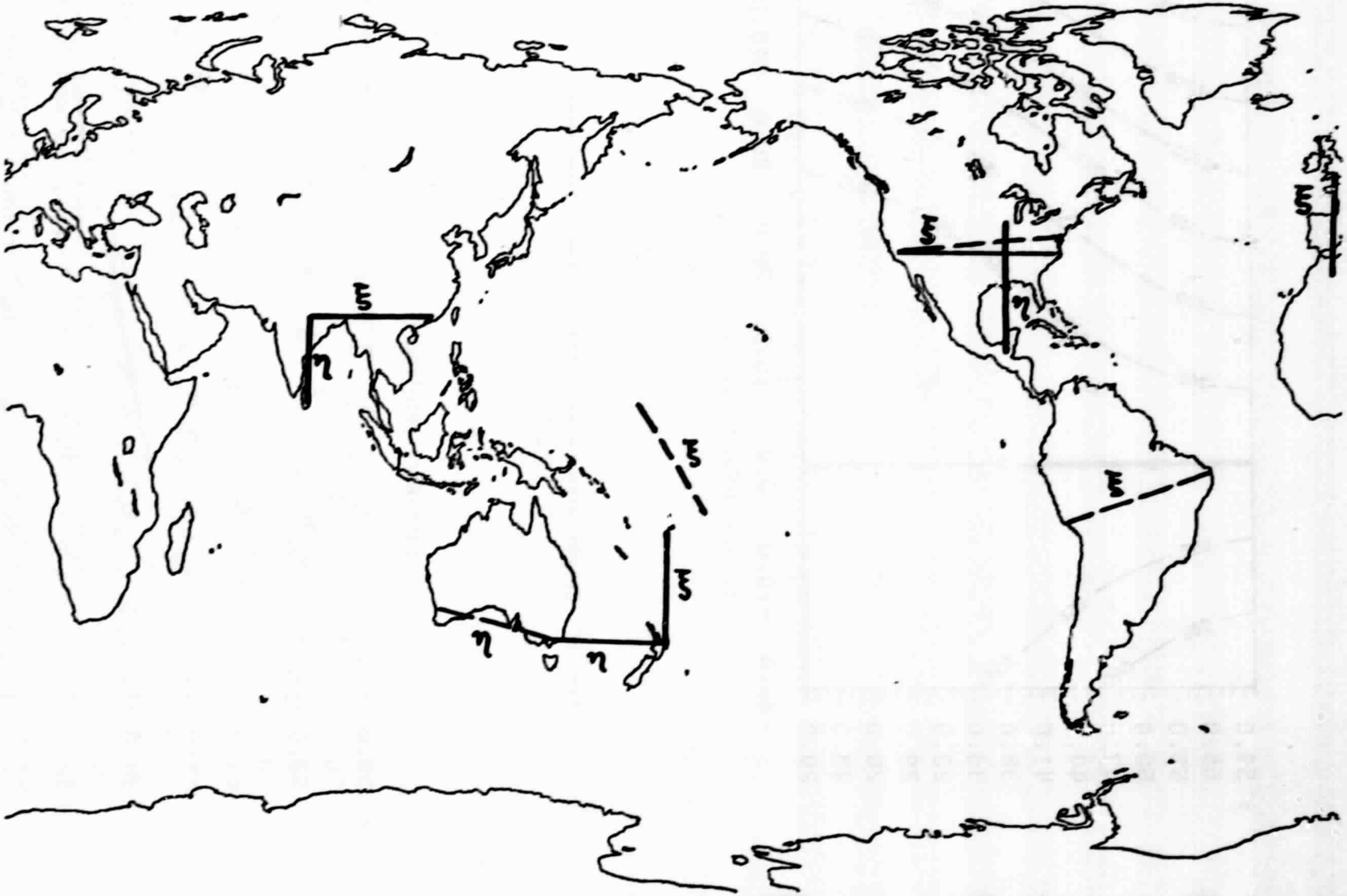


Fig. 8 Baseline distribution for polar motion variation determinations. (Dashed lines denote already existing baselines.)



It is quite unfortunate that although several of the existing laser stations fulfill the optimization requirements, commonly observed passes between them are very sparse. The lack of a long time period during which these stations co-observe Lageos makes it impossible to compare these results with those obtained by other techniques.

Reference Frames

The position of the observing stations is defined in a geocentric earth-fixed system which is materialized by a mean pole (e.g., CIO) and a mean Greenwich meridian (e.g., BIH). The observations are tagged with UTC epochs. The link between this system and the inertial system is provided by the Greenwich hour angle of the true vernal equinox and the coordinates of the true celestial pole with respect to the mean pole used. The link between the inertial frame for the integration of the orbit and the true of date frame at the observational epochs is provided by the precession and nutation theories of Lieske [1979] and Wahr [1979] respectively. The time scales involved, UT1 and UTC are related to each other using the difference Δ(UT1 - UTC) as obtained from JPL [Fliegel, 1981].

Gravitational Perturbations

The perturbations due to the Earth's gravitational field are computed based on the formulation given in [Cappellari et al., 1976]. There is, however, a subtle point in the coordinate system transformations involved which deserves further explanation, especially in view of the existing confusion [Reigber, 1981]. This will be dealt with in the next section. The point mass accelerations due to the attraction of the moon, the sun, and the planets Venus, Mars, Jupiter and Saturn can be included at option in our current software. The planetary ephemerides, as well as the lunar and solar position vectors, are obtained by interpolation from the JPL tape containing the DE114 Solar, Lunar and Planetary Ephemeris [Standish, 1981].

Computation of the Non-Spherical Effects from the Terrestrial Gravitation

The gravitational potential is expressed as a series expansion in spherical harmonics. With the 0^{th}-order term (point mass effect) removed, we can write the non-spherical part of it as:

$$V(r,\phi,\lambda) = \frac{GM}{r}\sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{a_e}{r}\right)^n [S_{nm}\sin m\lambda + C_{nm}\cos m\lambda]\, P_{nm}(\sin\phi) \tag{1}$$

where r,ϕ,λ are the spherical coordinates of the point of evaluation. From the purely mathematical point of view the choice or definition of the (r,ϕ,λ) system is irrelevant. The function V, the potential, which is approximated by the series is invariant with respect to any similarity transformation of the underlying coordinate system; the value of V at $P(r,\phi,\lambda)$, V_p will be the same whether P is defined in the (r,ϕ,λ) system or, say, the (r',ϕ',λ') system. The series, however, in (r',ϕ',λ') will have different constants, harmonics, in this case. It is thus obvious that the similarity transformation between (r,ϕ,λ) and (r',ϕ',λ') propagates as a similarity transformation between (C_{nm}, S_{nm}) and (C'_{nm}, S'_{nm}).

So far, the above is just a restatement of already known facts. For instance, Kleusberg [1980] has developed the (rather cumbersome) formulae to obtain the primed harmonics from the original, given the transformation parameters. It is the last statement in the previous paragraph that causes the problems: The fact that a change in the coefficients cannot be attributed to an actual change of the coefficient or a coordinate system change, unless it is known a priori which of the two happened. In a sense this is similar to "the principle of equivalence" in general relativity, whereby gravitational and inertial forces are inseparable. Considering now that in a dynamical solution the coordinate system definition is provided by the satellite dynamics (short of a longitude definition), one realizes how important it is to clearly define a priori the system in which the harmonics of the series in (1) are referenced.

It is a well known fact [Heiskanen and Moritz, 1967; Nagel, 1976] that for the low-degree harmonics (up to n=2) we can easily associate with them certain properties of the estimated model. The pair (C_{21}, S_{21}) is of particular interest to us since their values are directly proportional to the alignment of the reference system with the principal axis of maximum moment of inertia. Lambeck first called attention to the implications of this otherwise innocent looking property, in [Lambeck, 1971], where he stated that

$$u^* = \frac{C_{21}}{C_{20}} \qquad \text{and} \qquad v^* = -\frac{S_{21}}{C_{20}} \tag{2}$$

u^* and v^* being the coordinates of the axis of figure with respect to the third axis of the reference coordinate system (the axes u^*, v^* are defined

in the same sense as the x_p, y_p for the pole). A proof for (2) can be found in [Nagel, 1976]. This interesting property becomes a real problem in practice, due to the fact that the axis of figure is time variant. In [McClure, 1973; Nagel, 1976; Leick, 1978; and Moritz, 1979], one will find detailed descriptions of the motions of this axis. It suffices here to mention that there is a free motion with an amplitude of 2 m and a period equal to that of the Chandlerian wobble (~430 days) and a forced diurnal motion with an amplitude equal to 60 m!

To include at least the long period effect in the harmonics C_{21} and S_{21} implies that the coordinates of the center of the Chandlerian wobble are known. Since there are only known from observations, one has to rely on some predictions based on the past motion of the center. Given those, then the instantaneous values of the two harmonics can be computed from relatively simple formulae:

$$\begin{aligned} C_{21}^{i} &\approx \{\bar{x} + \tfrac{1}{3}(x_p - \bar{x})\}\, C_{20} \\ S_{21}^{i} &\approx -\{\bar{y} + \tfrac{1}{3}(y_p - \bar{y})\}\, C_{20} \end{aligned} \qquad (3)$$

From some simple computations, the effect of the aforementioned motion of the axis of figure on C_{21} and S_{21} seems to be capable enough to cause apparent accelerations of the order of 10^{-12} m/sec^2 on Lageos, for a change of a few tens of milli-arcseconds in the polar coordinates (a value quite reasonable for a five-day interval). We are currently investigating the implications of such an acceleration.

Results and Conclusion

As it was mentioned before, although very realistic simulation studies have indicated that the proposed method can produce virtually bias free polar motion variations, the lack of well distributed real data makes it impossible to deduce anything conclusive about it. As far as formal precisions are concerned, it seems quite definite by now that a few milli-arcseconds can easily be achieved even for one-day averages. That, of course, is only a lower bound of no great significance as far as accuracy is concerned, but if biases can be minimized with this method then the real accuracy level will not be exceedingly

higher than this estimate. We have lately acquired the laser data collected during the short MERIT campaign, and it seems as if there are a number of more suitable data sets which can be used for testing the method, than that which we had earlier from the late 1979 to early 1980 data. Once this study is completed, we should have more definitive answers to present.

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APPENDIX 2

TRIP REPORT

IUGG/IAG VIth International Symposium on Geodetic Networks and Computations, Munich, August 31 - September 5, 1981
Programme

"Geodesy and the Global Positioning System"
by Ivan I. Mueller and Brent Archinal

Minutes of CSTG Meetings, Munich, September 2, 1981

APPENDIX 3

TRIP REPORT

VIII Hotine Symposium on Mathematical Geodesy
Como, Italy
September 7-9, 1981

Program

TENTATIVE SCIENTIFIC PROGRAM

MONDAY - SEPT. 7

I - 9:00-10:20

CHOVITZ B.	- The influence of Hotine's "Mathematical Geodesy".
GEORGIADOU Y.	- Love numbers and the deformation of gravity space.
BODE A. GRAFAREND E.W.	- The telluroid mapping based on a normal gravity potential including the centrifugal term.
OLIVIERATOS V. DERMANIS A. PARASCHACHIS I.	- Dilatation, shear and rotation analysis of map projections.

I - 10:50-12:30

BOCCHIO F.	- On the inverse geodetic singularity problem.
GRAFAREND E. W.	- The small scale structure of geometry and gravity space.
BRUNNER F. K.	- Appraisal of the geometrical optics approximation for geodetic refraction calculations.
BOUCHER C.	- Review of relativistic effects in the Solar System and their impact on geodetic models.
WEIGHTMAN J. A.	- Datum transformation from data within a limited area.

II - 14:30-16:30

BAARDA W.	- Some comments on "A connection between geometric and gravimetric geodesy".
REMMER O.	- Two letters on physical geodesy.
EEG J.	- Continuous methods in least squares theory.
ADAM J.	- On the determination of similarity coordinate transformation parameters.
KELM R.	- Modelling of the gravity field effects on geometric parameters in local networks.
FRITSCH D. SCHAFFRIN B.	- The "choice of norm" problem for the free net adjustment with orientation parameters.

II - 16:50-18:30

SVENSSON L.	- On a new geodesy based upon inversionfree Bjerhammar predictors.
BJERHAMMAR A.	- On the collocation solution for a non-spherical surface.
BERTOTTI B.	- Higher order correlation functions for the gravity field.
SCHWARZ K. P. LACHAPELLE G. MAINVILLE A.	- Investigations into the anisotropy and non-homogeneity of the gravity anomaly field.
DUFOUR H. M.	- La correction de Rudzki améliorée. Justifications. Applications.
CAPUTO M.	- Physical constraints for the estimate of strain on the Earth's surface.

TUESDAY - SEPT. 8

III - 14:30-16:30

FELL P.	- Decreasing the influence of distant zones with modifications to the Stokes and Vening Meinesz Kernels.
GERSTL M.	- Numerical evaluation of elliptic integrals for some geodetic applications.
FREEDEN W.	- On interpolation by harmonic splines.
KLEUSBERG A.	- Cartesian representation of the gravitational field.
NAGY D.	- Direct gravity formulae for the GRS 1980: a revew.
HOFMANN-WELLENHOF B. MEISSL P.	- Applications of sparse matrix techniques to physical geodesy.

III - 16:50-18:30

TSCHERNING C.C. PODER K.	- Some geodetic applications of Clenshaw summation.
RUMMEL R.	- Estimation of gravity field parameters with stabilized integral Kernels.
KRYNSKI J.	- Processing of satellite-to-satellite tracking data for gravity field determination.
PETROVSKAYA M.	- Representation of the Earth's potential by convergent series.
COLOMBO O. L.	- Convergence problems in spherical harmonic expansions.

WEDNESDAY - SEPT. 9

IV - 9:00-10:40

ENGL H. - On the parameter choice problem in regularization methods for solving linear ill-posed problems.

HOLOTA P. - On geodetic impropoerly posed problems and the subgroup of IAG SSG 4.57.

~~NEYMAN Y. M. - Improperly posed geodetic problems.~~

PAGANI C. - An inverse problem in potential theory.

SANSO' F. - A note on density problems and the Runge-Krarup's theorem.

IV - 11:00-12:40

BOSCH W. - Some remarks to the geopotential, its boundary values and the topography of the Earth.

PELLINEN L. P. - Effects of the Earth's ellipticity in solving geodetic boundary value problems.

WITSCH K. J. - On the free boundary value problem of physical geodesy.

SJÖBERG L. - On the altimetry-gravimetry boundary problem.

DERMANIS A.
SANSO' F. - The geodynamic boundary value problem.

14:30-16:00

The class-room will be at disposal for informal discussions.

16:30-18:30

Meeting of the S.S.G. 4.57

International Union of Geodesy and Geophysics

– International Association of Geodesy –

SYMPOSIUM ON GEODETIC NETWORKS AND COMPUTATIONS

(VIth International Symposium on Geodetic Computations)

MUNICH, August 31 – September 5, 1981

Deutsche Geodätische Kommission (DGK)
bei der Bayerischen Akademie der Wissenschaften

Deutsches Geodätisches Forschungsinstitut (DGFI),
Zentralleitung und Abteilung I, München

Bayerische Kommission für die Internationale Erdmessung (BEK)
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Financial support for this Symposium has been granted generously by Deutsche Forschungsgemeinschaft und by Bayerische Staatsregierung.

PROGRAMME

MONDAY 31 AUGUST

TIME
MORNING

8.00	Reception of participants, registration
10.30	Festive Opening Session
12.30	Lunch break

AFTERNOON, 14.30 - 17.30
SESSION I

OBJECTIVES OF GEODETIC NETWORKS, STATUS REPORTS, FUTURE PLANS

TIME
AFTERNOON

14.30 OPENING OF THE 1. WORKING SESSION: *A. R. Robbins*

CHAIRMAN: *C. Boucher, Institut Géographique National - St. Mandé (France)*

14.40 REVIEW PAPER: OBJECTIVES OF GEODETIC NETWORKS AND FUTURE PLANS
H. Wolf, Universität Bonn (Fed.Rep. of Germany)

15.00 I.1. A PRELIMINARY GEOID FOR SOUTH-EAST ASIA AND THE PACIFIC
J.S. Allman, University of New South Wales (Australia), J. B. Steed, Division of National Mapping - Canberra (Australia)

I.2. CURRENT STATUS OF THE NORTH AMERICAN SUBCOMMISSION OF COMMISSION X
J.D. Bossler, National Geodetic Survey - US Dept. of Commerce - Rockville (USA)
(Presented by J. Gergen, National Geodetic Survey - Rockville (USA))

I.3. STATUS OF RETRIG

E.H. Messerschmidt, Bayer. Landesvermessungsamt - München (Fed. Rep. of Germany)

I.4. STATUS AND PROVISIONAL RESULTS OF THE 1981 ADJUSTMENT OF THE UNITED EUROPEAN LEVELLING NETWORK UELN - 73

W. Ehrnsperger, Bayerische Komm. für die Internationale Erdmessung - München (Fed. Rep. of Germany),
J.J. Kok, University of Delft (Netherlands),
J. van Mierlo, Universität Karlsruhe (Fed.Rep.of Germany);

16.00 Coffee break

16.30 I.5. STATE OF GEODETIC NETWORKS IN AFRICA - RESULTS AND FUTURE PLANS

R.O. Coker, Hunting Africa Resource Service Ltd. - Lagos (Nigeria)

I.6. DESIGN OF A GLOBAL GEODETIC NETWORK FOR GEODYNAMICS

H. Drewes, Deutsches Geodätisches Forschungsinstitut - München (Fed. Rep. of Germany)

I.7. IMPROVEMENT AND READJUSTMENT OF MAJOR GEODETIC HORIZONTAL NETWORK IN ISRAEL

R. Adler/ G. Galod, Survey of Israel - Tel Aviv (Israel)

I.8. STATUS OF THE ADJUSTMENT OF THE PRECISE GEODETIC NETWORK IN JAPAN

M. Ishihara, Geographical Survey Institute (Japan)

OTHER CONTRIBUTIONS (ONLY FOR SYMPOSIUM PROCEEDINGS):

1. GEODETIC NETWORK SURVEYS IN THE PHILIPPINES
N.B. Akilit/ E.B. Bautista, Bureau of Lands - Manila (Philippines)

2. ESTABLISHMENT OF A FIRST ORDER GRAVITY NETWORK IN NORTHERN GREECE
D. Arabelos/ I.N. Kerrinti/ L.N. Mavridis, University of Thessaloniki (Greece)

3. ESTABLISHMENT OF A HIGH PRECISION GRAVITY NETWORK IN THE AREA OF THESSALONIKI
A. Badellas/ A. Gounaris/ L.N. Mavridis, University of Thessaloniki and University of Thrace (Greece)

4. THE GEODETIC ACTIVITIES OF THE WORKING GROUP ON GEODESY AND CARTOGRAPHY OF THE SCIENTIFIC COMMITTEE OF ANTARCTIC RESEARCH
A.G. Bomford, Div. of National Mapping - Queanbeyan (Australia)

5. a) OBJECTIVOS DE REDES GEODESICAS
   b) INFORME SOBRE ACTIVIDADES DEL INSTITUTO GEOGRAFICO MILITAR ARGENTINO
L.J. Borelli, Instituto Geografico Militar - Buenos Aires (Argentina)

6. THE DEVELOPMENT OF A NATIONAL GEODETIC INFORMATION SYSTEM
L.A. Fuentes U./ F. Hansen, Dirección General de Geografía del Territorio Nacional, Secretaría de Programación y Presupuesto - México (México)

7. LEVELLING NETWORK OF CROATIA
St. Klak, Geod. Fakultät Sveucilista u Zagrebu (Yugoslavia)

8. STATUS OF THE ESTABLISHMENT OF VERTICAL DATUM AND THE LEVEL NET IN INDIA
U.K. Nagar/ M.G. Arur/ K.L. Khosla, Survey of India - Dehra Dun (India)

9. NETWORK READJUSTMENT IN INDONESIA (STATUS REPORT)
J. Rais, National Mapping - Jakarta (Indonesia)

10. ARBEITEN ZUR ERNEUERUNG DES DEUTSCHEN HAUPTDREIECKSNETZES
R. Schmidt, Landesvermessungsamt Nordrhein-Westfalen - Bonn (Fed. Rep. of Germany)

18.00 WELCOME BY THE BAVARIAN GOVERNMENT

TUESDAY 1 SEPTEMBER

MORNING, 8.30 – 12.30

SESSION II

OPTIMAL DESIGN OF GEODETIC NETWORKS (ACCURACY, RELIABILITY, COSTS, ETC.)

TIME
MORNING

8.30 CHAIRMAN: *R.A. Cross, North East London Polytechnic (England)*
REPORT OF SSG 1.59: COMPUTER AIDED DESIGN OF GEODETIC NETWORKS

8.40 REVIEW PAPER: OPTIMAL DESIGN OF GEODETIC NETWORKS
G. Schmitt, Universität Karlsruhe (Fed. Rep. of Germany)

9.00 II.1. OPTIMIZATION OF OBSERVING LOGISTICS IN GEODETIC NETWORKS
E.G. Anderson/ R. Steeliker, Surveying Engineering, University of Calgary (Canada)

II.2. OPTIMAL DESIGN OF GEODETIC NETWORKS
S. Berendorf, Instituto Geografico Militar - Buenos Aires (Argentina)

II.3. ON THE DESIGN OF GEODETIC NETWORKS USING ITERATIVE METHODS
R.A. Cross/ M.B. Whiting, North East London Polytechnic (England)

II.4. SECOND ORDER DESIGN OF GEODETIC NETWORKS
PROBLEMS AND EXAMPLES
D. Fritsch, Universität Bonn (Fed. Rep. of Germany)

10.00 Coffee break

10.30 II.5. AN INVESTIGATION ON THE OPTIMIZATION OF THE SPACE OBJECTS OBSERVATIONS FOR THE EAST-EU: ?EAN SATELLITE-TRIANGULATION

N.T. Georgiev, Central Laboratory for Geodesy - Sofia (Bulgaria)

II.6. OPTIMIZATION OF GEODETIC NETWORK

E.W. Grafarend, Universität Stuttgart (Fed. Rep. of Germany)

II.7. OPTIMIZATION OF THE CONFIGURATION OF GEODETIC NETWORKS

K.R. Koch, Universität Bonn (Fed. Rep. of Germany)

II.8. INTERACTIVE NETWORK ANALYSIS

M.P. Mepham/ E.J. Krakiwsky, University of Calgary (Canada)

II.9. SOME CONSIDERATIONS ON THE OPTIMAL DESIGN OF GEODETIC NETWORKS

B. Schaffrin, Universität Bonn (Fed. Rep. of Germany)

II.10. SECOND ORDER DESIGN OF GEODETIC NETWORKS BY AN ITERATIVE APPROXIMATION OF A GIVEN CRITERION MATRIX

H. Wimmer, Technische Universität München (Fed. Rep. of Germany)

OTHER CONTRIBUTIONS (ONLY FOR SYMPOSIUM PROCEEDINGS)

1. OPTIMIZATION OF A LOCAL CONTROL NET FOR GEODYNAMICS

   G. Boedecker/ H. Uelsinck, Deutsches Geodätisches Forschungsinstitut-München (Fed. Rep. of Germany)

2. POSSIBILITIES FOR THE STRENGTH IMPROVEMENT OF THE HELLENIC FIRST ORDER TRIANGULATION NETWORK

   A.Dermanis/A.Fotiou/D.Rossikopoulos,University of Thessaloniki (Greece)

3. EXPERIENCES IN APPLYING GEODETIC NETWORK OPTIMIZATION

   T. Ninkov, Inst. za Geodeziju - Beograd (Jugoslavia)

4. REPORT OF SSG 4.71: OPTIMIZATION OF GEODETIC NETWORKS (PRESENTATION IN SSG 4.71 - MEETING)

   G.Schmitt, Universität Karlsruhe (Fed. Rep. of Germany)

5. TREE-SEARCH ALGORITHM FOR THE TRIANGULATION-TRILATERATION COST MINIMIZATION

   C. Tsouros, University of Thessaloniki (Greece)

12.30 Lunch break

TUESDAY 1 SEPTEMBER

AFTERNOON , 14.30 - 17.30

SESSION III

MODERN OBSERVATION TECHNIQUES FOR TERRESTRIAL NETWORKS (SATELLITE AND INERTIAL TECHNIQUES, VLBI, ALTIMETRY, ETC.)

TIME
AFTERNOON

14.30 CHAIRMAN: *I.I. Mueller, Ohio State University - Columbus (USA)*

14.40 REVIEW PAPER: SPACE TECHNIQUES FOR TERRESTRIAL NETWORKS
J. Gergen, National Geodetic Survey - Rockville (USA)

15.00 III.1. THE ATMOSPHERIC EFFECTS ON ELECTROMAGNETIC DISTANCE MEASUREMENTS IN GEODETIC NETWORKS
F. K. Brunner, Univ. of New South Wales - Kensington (Australia)

III.2. GEODESY AND THE GLOBAL POSITIONING SYSTEM
I.I. Mueller, Ohio State University - Columbus (USA)

III.3. USE OF SATELLITE-DOPPLER OBSERVATIONS FOR GEODETIC NETWORKS
V. Ashkenazi/ S. Grist, University of Nottingham (England)

III.4. NEW METHODS FOR THE REDUCTION OF SATELLITE DATA APPLICABLE TO GEODESY
G.E. Giacaglia, Dept. of Mechanical Engineering - Sao Paulo (Brasil)

16.00 Coffee break

16.30 III.5. CONSEQUENCES OF GRAVSAT AND GPS: NEW CONCEPTS OF GEODETIC NETWORKS

E. Groten / B. Stock, Technische Universität Darmstadt (Fed. Rep. of Germany)

III.6. ON THE USE OF ORBITAL METHODS FOR DEVELOPMENT OF SATELLITE GEODETIC NETWORKS

N.I. Georgiev, Central Laboratory for Geodesy - Sofia (Bulgaria)

OTHER CONTRIBUTIONS (ONLY FOR SYMPOSIUM PROCEEDINGS):

1. ESTABLISHMENT OF A BASE LINE OVER THE SEA
   A. Badellas / P. Savaidis / J. Ifantis, University of Thessaloniki (Greece)

2. REPORT ON THE WORK OF SSG 1.42: ELECTROMAGNETIC WAVE PROPAGATION AND REFRACTION IN THE ATMOSPHERE
   F.K. Brunner, University of New South Wales - Kensington (Australia) (Presentation in the SSG-Meeting)

3. REPORT OF THE SSG 1.26: CONTRIBUTIONS FROM SATELLITE GEODESY TO TERRESTRIAL GEOMETRIC GEODESY
   J. Kakkuri, Geodetic Institute - Helsinki (Finland)

4. ON THE TRIGONOMETRIC LEVELLING
   T. Parm, Finnish Geodetic Institute - Helsinki (Finland)

17.30 END OF WORKING SESSION, CONTINUATION FRIDAY SEPTEMBER 4 IN SESSION VIII

19.00 Visit of the Bavarian State Collection of Painting

WEDNESDAY 2 SEPTEMBER

MORNING AND AFTERNOON, 8.30 - 12.30 and 14.30 - 17.00

SESSION IV

NETWORK ANALYSIS MODELS (BLUNDERS, SYSTEMATIC ERRORS, STATISTICAL TESTS, DEFORMATIONS, ETC.)

TIME
MORNING

8.30 CHAIRMAN: *J. van Mierlo, Universität Karlsruhe (Fed. Rep. of Germany)*

8.40 REVIEW PAPER: DIFFERENT ASPECTS FOR THE ANALYSIS OF GEODETIC NETWORKS
K.R. Koch, Universität Bonn (Fed.Rep.of Germany)

9.00 IV.1. A REVIEW OF MODEL CHECKS AND RELIABILITY
J. van Mierlo, Universität Karlsruhe (Fed. Rep. of Germany)

IV.2. EXPERIENCES WITH A NONSTATISTICAL METHOD OF DETECTING OUTLIERS
G. Heindl, Universität - Gesamthochschule Wuppertal, E. Reinhart, Institut für Angewandte Geodäsie - Frankfurt (Fed. Rep. of Germany)

IV.3. ADJUSTMENT BY MINIMIZING THE SUM OF ABSOLUTE RESIDUALS
H. Fuchs, Universität Graz (Austria)

IV.4. RELIABILITY AND GROSS ERROR DETECTION IN PHOTOGRAMMETRIC BLOCKS
F. Ackermann, Universität Stuttgart (Fed. Rep. of Germany)

10.00 Coffee break

10.30 IV.5. ON THE RELIABILITY OF 3RD AND 4TH ORDER NETWORK DENSIFICATION
W. Förstner, Universität Stuttgart (Fed. Rep. of Germany)

IV.6. ACCURACY ANALYSIS OF THE FINNISH LASER GEODIMETER TRAVERSE
J. Kakkuri/ T. Parm, Finnish Geodetic Institute - Helsinki (Finland);
V. Ashkenazi/ S.A. Crane, University of Nottingham (England)

IV.7. COMBINED LEAST SQUARES SOLUTION OF TERRESTRIAL AND DOPPLER OBSERVATIONS
D. Ehlert, Institut für Angewandte Geodäsie - Frankfurt (Fed. Rep. of Germany)

IV.8. ERROR PROPAGATION IN LEVELLING NETWORKS
H. Pelzer, Universität Hannover (Fed. Rep. of Germany)

IV.9. THE BINOMIAL DISTRIBUTION AS PROBABILITY MODEL OF THE DISTRIBUTION OF ERRORS OF GEODETIC OBSERVATIONS
M.K. Szacherska, University of Olsztyn (Poland)

IV.10. A METHOD FOR DETECTING VERTICAL SOIL MOVEMENTS FROM SCATTERED LEVELLING NETS. APPLICATION ON FIRST PRECISE LEVELLING NETS OF HAMBURG
R. Heer/ T. Leonhard, Universität Hannover (Fed. Rep. of Germany)

IV.11. ON THE OPTIMIZATION OF LEVELLING NETWORKS WITH RESPECT TO THE DETERMINATION OF CRUSTAL MOVEMENTS
W. Niemeier, Universität Hannover,(Fed. Rep. of Germany)

IV.12. PRECISE LEVELLING ACROSS ACTIVE FAULTS IN CALIFORNIA
A.G. Sylvester, Dep. of Geological Sciences, University of California - Santa Barbara (USA)

12.30 Lunch break

AFTERNOON

14.30 IV.13. THE EFFECT OF THE VARIATION OF THE DESIGN IN A LARGE NETWORK, DEMONSTRATED FOR BLOCK D OF RETRIG

H. Hornik, Deutsches Geodätisches Forschungsinstitut - München (Fed. Rep. of Germany)

IV.14. DESCRIPTION OF HORIZONTAL STRAINS AND SOME GEODETIC ASPECTS OF THEIR ANALYSIS

W. Welsch, Hochschule der Bundeswehr - München (Fed. Rep. of Germany)

IV.15. LEAST SQUARES PREDICTION OF HORIZONTAL COORDINATE DISTORTIONS IN CANADA

G. Lachapelle/ A. Mainville, Sheltech - Calgary (Canada)

IV.16. CRUSTAL DEFORMATION OF THE AUSTRALIAN PLATE MEASURED BY SATELLITE LASER RANGING: PRELIMINARY RESULTS

A. Stolz/ R.W. Angus-Leppan/ E.G. Masters/ B. Hirsch, University of New South Wales - Kensington (Australia)

15.30 Coffee break

IV.17. THREE-DIMENSIONAL KINEMATICS OF EARTH DEFORMATION FROM GEODETIC OBSERVATIONS

W.I. Reilly, Geophysics Division, Dep. of Scientific and Industrial Research - Wellington (New Zealand)

IV.18. ANALYSE STATISTIQUE DE LA DEFORMATION DES RESEAUX

H.M. Dufour, Institut Géographique National - Saint Mandé (France)

IV.19. GEODETIC PREDICTION OF ACTUAL CRUSTAL DEFORMATIONS AT THE SEISMIC AREA OF VOLVI

A. Dermanis/ E. Livieratos/ D. Rossikopoulos/ D. Vlachos, University of Thessaloniki (Greece)

IV.20. STRENGTH ANALYSIS OF ANGULAR ANBLOCK NETWORKS WITH DISTANCE MEASUREMENTS ALONG THE PERIMETER

R. Meissl, Universität Graz (Austria)

OTHER CONTRIBUTIONS (ONLY FOR SYMPOSIUM PROCEEDINGS)

1. ON THE POINT IDENTITY PROBLEM IN CONTROL NETWORKS
   W. Augath / W. Niemeier, Universität Hannover (Fed. Rep. of Germany)

2. TECHNIQUES OF STATISTICAL ANALYSIS AS APPLIED TO GEODETIC ADJUSTMENT COMPUTATIONS
   R.M. Gupta, Research & Development Dte, Survey of India - Hyderabad (India)

3. HEIGHT DEPENDENT ERRORS IN SOUTHERN CALIFORNIA LEVELING DATA
   D.D. Jackson, Dept. Earth and Space Sciences - Los Angeles (USA)

4. REPORT OF SSG 4.60: STATISTICAL METHODS FOR ESTIMATION AND TESTING OF GEODETIC DATA
   (Presentation in the SSG-Meeting)
   K.R. Koch, Universität Bonn (Fed. Rep. of Germany)

5. OPTIMIERUNG DES MESSPROZESSES
   (OPTIMIZATION OF THE MEASUREMENT PROCESSES)
   R. Mrkić, Institut za Geodeziju - Beograd (Yugoslavia)

6. STRAIN OF HORIZONTAL NETWORKS
   P. Vanicek, Dept. of Surveying - Fredericton (Canada)

17.30 City Tour

THURSDAY 3 SEPTEMBER

MORNING, 8.30 - 12.30

SESSION V

ADJUSTMENT PROCEDURES OF GEODETIC NETWORKS
(POINT AND INTERVAL ESTIMATION, VARIANCE AND
COVARIANCE COMPONENT ESTIMATION, ETC.)

TIME
MORNING

8.30 CHAIRMAN: *C. R. Schwarz, National Geodetic Survey - Rockville (USA)*

8.40 REVIEW PAPER: ADJUSTMENT PROCEDURES OF GEODETIC NETWORKS
E. Grafarend, Universität Stuttgart (Fed. Rep. of Germany)

9.00 V.1. MATHEMATICAL MODEL FOR NETWORK GEOMETRIC ADJUSTMENT
C. le Cocq/ C. Boucher, Institut Géographique National - Saint Mandé (France)

V.2. THE ESTIMATION OF COVARIANCE MATRICES FOR PHOTOGRAMMETRIC IMAGE COORDINATES
W. Förstner/ R. Schroth, Universität Stuttgart (Fed. Rep. of Germany)

V.3. ADJUSTMENT OF GEODETIC NETWORKS IN SPACE
A. Marussi, University of Triest (Italy)

V.4. ON FREE NET ADJUSTMENT ON THE ELLIPSOID
K. Schnädelbach, Technische Universität München (Fed. Rep. of Germany)

10.00 Coffee break

10.30 V.5. ON THE ADJUSTMENT OF CONTINENTAL VERTICAL GEOKINETIC NETWORKS
I.N. Totomanov, Central Laboratory for Geodesy - Sofia (Bulgaria)

V.6. COMBINED ADJUSTMENT OF DOPPLER AND TERRESTRIAL NETS IN DOPPLER REFERENCE SYSTEM
I. Gajderowicz, Institute of Geodesy and Photogrammetry ART - Olsztyn (Poland)

V.7. AN APPLICATION OF THE GRAPH THEORY IN THE ADJUSTMENT OF A GEODETIC NET
F. Crosilla/ G. Manzoni, Istituto di Strada e Trasporti - Università Trieste (Italy)

V.8. JUNCTION OF EUROPEAN DOPPLER OBSERVATION CAMPAIGNS CARRIED OUT BY THE IfAG/SFB 78
W. Schlüter, Institut für Angewandte Geodäsie - Frankfurt (Fed. Rep. of Germany)

V.9. AN INTRODUCTION TO THE ADJUSTMENT OF ASTRO-GEODETIC NETWORK OF THE PEOPLE'S REPUBLIC OF CHINA
D. Gu, Chinesische Gesellschaft für Geodäsie und Kartographie der Volksrepublik China - Baiwanzhuang, Beijing (China)

OTHER CONTRIBUTIONS (ONLY FOR SYMPOSIUM PROCEEDINGS):

1. REPORT OF SSG 1.69: COMPARISON OF CONTROL NETWORK ADJUSTMENT MODELS
V. Ashkenazi, University of Nottingham (England)

2. READJUSTMENT OF THE POLISH PRIMARY HORIZONTAL NETWORK
J. Gaździcki, Centrum Informatyczne Geodezji i Kartografii - Warsaw (Poland)

3. ANWENDUNG DER KOLLOKATION FÜR ZWEI GEMEINSAM ABHÄNGIGE STÜTZWERTE UND FÜR DIE IN DER EBENE LIEGENDEN STÜTZPUNKTE (ANWENDUNG DER KOLLOKATION ZUR BESTIMMUNG DER OBJEKTIVDISTORTION)
J. Kabeláč, Lehrstuhl f. Höhere Geodäsie-Praha (Czechoslovakia)

12.30 Lunch break

THURSDAY 3 SEPTEMBER

AFTERNOON, 14.30 - 17.30

SESSION VI

COMBINATION OF HORIZONTAL, VERTICAL AND GRAVITY NETWORKS (THREE AND FOUR DIMENSIONAL PROBLEMS, REDUCTIONS, ETC.)

TIME AFTERNOON		
14.30		CHAIRMAN: *W. Baarda, University of Delft (Netherlands)*
14.40		REVIEW PAPER: COMBINATION OF HORIZONTAL, VERTICAL AND GRAVITY NETWORKS - A REVIEW *R. Kelm, Deutsches Geodätisches Forschungsinstitut - München (Fed. Rep. of Germany)*
15.00	VI.1.	COMBINATION OF LEVELLING AND GRAVITY DATA FOR DETECTING REAL CRUSTAL MOVEMENTS *B. Heck, Universität Karlsruhe (Fed. Rep. of Germany)*
	VI.2.	A CONTRIBUTION TO 3D-OPERATIONAL GEODESY *G.W. Hein, Techn. Universität Darmstadt (Fed. Rep. of Germany)*
	VI.3.	ORIENTATION INFORMATION OF LEVELLING AND GRAVITY MEASUREMENTS IN THREE-DIMENSIONAL REGIONAL NETWORKS *R. Kelm, Deutsches Geodätisches Forschungsinstitut - München (Fed. Rep. of Germany)*
	VI.4.	AN ASTRO-GRAVIMETRIC COMPUTATION OF THE QUASI-GEOID OF THE FEDERAL REPUBLIC OF GERMANY *D. Lelgemann / D. Ehlert / H. Hauck, Institut für Angewandte Geodäsie - Frankfurt (Fed. Rep. of Germany)*
16.00	Coffee break	

16.30	VI.5.	ON THE INTERPOLATION OF GRAVITY ANOMALIES AND DEFLECTIONS OF THE VERTICAL IN MOUNTAINOUS TERRAIN *H. Baussus von Luetzow, U.S. Army Topographic Laboratories (USA)*
	VI.6.	TEST-COMPUTATIONS OF THREE-DIMENSIONAL GEODETIC NETWORKS WITH OBSERVABLES IN GEOMETRY AND GRAVITY SPACE *E. Grafarend/ J. Zaiser, Universität Stuttgart (Fed. Rep. of Germany)*
	VI.7.	THREE-DIMENSIONAL ADJUSTMENT OF GEODETIC NETWORKS USING GRAVITY FIELD DATA *W. I. Reilly, Geophysics Division, Dep. of Scientific and Industrial Research - Wellington (New Zealand)*
17.30	End of Working Session	
17.30	Departure to Castle Lustheim	
20.15	Serenade at Castle Schleißheim	

FRIDAY 4 SEPTEMBER

MORNING, 8.30 - 12.30

SESSION VII

COMPUTATIONAL PROBLEMS IN CLASSICAL AND NON-CLASSICAL ADJUSTMENT MODELS (LARGE NETWORKS, ILL CONDITIONING, COLLOCATION, SOFTWARE PROBLEMS, ETC.)

TIME

MORNING

8.30 CHAIRMAN: *M. Odlanicki-Poczobutt, Instytut Geodezji Gorniczej i Przemyskowej AGH-Krakow (Poland)*

REPORT OF SSG 1.21:NUMERICAL COMPUTATION OF LARGE TRIANGULATION NETWORKS (together with *A. Plstek)*

8.40 REVIEW PAPER: COMPUTATIONAL PROBLEMS IN CLASSICAL AND NON-CLASSICAL ADJUSTMENT MODELS

K. Poder, Geodetic Institute - Charlottenlund (Denmark)

9.00 VII.1. REPORT ON CONCLUSIONS OF THE SYMPOSIUM "MANAGEMENT OF GEODETIC DATA"

C.C. Tscherning, Geodetic Institute - Charlottenlund (Denmark)

VII.2. AUTOMATED SET-UP AND ADJUSTMENT OF TRAVERSE NETWORKS

N. Bartelme, Technische Universität Graz (Austria)

VII.3. UNIVERSAL PROGRAM FOR ADJUSTMENT OF ANY GEODETIC NETWORK AND FOR CRUSTAL STRAINS

T. Harada, Pacific Aero Survey Co., Ltd. Tokyo (Japan)

VII.4. PROGRAM SYSTEM "NETZ" FOR THE ADJUSTMENT AND ANALYSIS OF LARGE GEODETIC NETWORKS USING SPARSE ALGORITHMS

M. Stark/ L. Gründig/ J. Bahndorf, Universität Stuttgart (Fed. Rep. of Germany)

10.00 Coffee break

10.30 VII.5. SPARSE MATRIX ALGORITHMS "NESTED DISSECTION" AND "MINIMUM DEGREE ORDERING" APPLIED TO DHM GENERATION

F. Steidler, Technische Universität München;
H. Stark, Universität Stuttgart (Fed. Rep. of Germany)

VII.6. SOME NEW PROCEDURES OF THE SEQUENTIAL ADJUSTMENT

W. Baran, Instytut Geodezji i Fotogrametrii - Olsztyn (Poland)

VII.7. CHOIX DE METHODE DE CALCUL EN ESTIMATION DES PARAMETRES SELON BAYES

I. Irencov/ N. Petrova, Central Laboratory for Geodesy - Sofia (Bulgaria)

VII.8. THE INCOMPLETE CHOLESKY CONJUGATE GRADIENT METHOD FOR NETWORK ADJUSTMENT

F. Sansò/ D. Benciolini/ L. Mussio, Istituto di Topografia, Fotogrammetria e Geofisica - Milano (Italy)

VII.9. THE OPTIMIZATION OF LARGE TRAVERSE NETWORKS

A. Plated, University of Mining and Metallurgy - Cracow (Poland)

VII.10. COMPUTATIONAL PROBLEM IN THE INDONESIAN-MALAYSIAN INTERNATIONAL BOUNDARY PROJECT

D. T. Saptodewo, Nat. Coord. Agency for Surveys and Mapping - Jakarta (Indonesia)

VII.11. ORDERING AND DISSECTION OF GEODETIC LEAST SQUARES EQUATIONS

K. Poder/ A.N. Mark, Geodetic Institute - Charlottenlund (Denmark)

OTHER CONTRIBUTIONS (ONLY FOR SYMPOSIUM PROCEEDINGS)

1. AN AUTOMATED THREE DIMENSIONAL ANALYSIS OF DEFORMATIONS FOR CONTROL OF BUILDINGS

   J. Bahndorf/ L. Gründig, Universität Stuttgart (Fed. Rep. of Germany)

2. AN ALGORITHM FOR THE INVERSION OF THE CORRELATED OBSERVATIONS COVARIANCE MATRICES
J. Casaca, Laboratorio Nacional de Engenharia Civil - Lisboa (Portugal)

3. A CONTRIBUTION TO THE TREATMENT OF DEFECTS IN LARGE GEODETIC NETWORKS
G. Funke / W. Weise, Universität Hannover (Fed. Rep. of Germany)

4. LEAST SQUARES ADJUSTMENT OF LARGE-SCALE GEODETIC NETWORKS BY SPARSE ORTHOGONAL DECOMPOSITION
R.J. Plemmons, University of Tennessee (USA)

5. ESTIMATION DE LA CONDITIONNALITE NUMERIQUE DES MATRICES NORMALES, OBTENUES EN COMPENSATION DES RESEAUX DE NIVELLEMENT
Z. Trencov, Central Laboratory for Geodesy - Sofia (Bulgaria)

12.30 Lunch break

FRIDAY 4 SEPTEMBER

AFTERNOON, 14.30 - 17.00

SESSION VIII

CONTINUATION OF TOPIC 5

MODERN OBSERVATION TECHNIQUES FOR TERRESTRIAL NETWORKS (INERTIAL TECHNIQUES, VLBI, ETC.)

TIME

AFTERNOON

14.30 VIII.1. USE OF INERTIAL TECHNIQUES FOR GEODETIC NETWORKS
A. Mancini, Research Analysis Division - Gimrada (USA)

VIII.2. ADJUSTMENT PROBLEMS IN INERTIAL POSITIONING
K.P. Schwarz/ M. Gauthier, University of Calgary (Canada)

VIII.3. WHAT INFORMATION CAN YOU GET OUT OF AN INERTIAL SURVEY SYSTEM, AND WHAT CAN YOU DO WITH IT?
M. van den Herrewegen, Institut Géographique National - Bruxelles (Belgium)

VIII.4. ORIENTATION OF SETS OF DIRECTIONS BY GYROSCOPIC MEASUREMENTS
W. Caspary/ H. Heister/ R. Schwintzer, Hochschule der Bundeswehr - München (Fed. Rep. of Germany)

15.30 Coffee break

16.00 VIII.5. USE OF INTERFEROMETRIC METHODS FOR GEODETIC HORIZONTAL NETWORKS
M.T. Prilepin, Soviet Geophysical Committee - Moscow (USSR)

VIII.6. MEASURES FOR PRECISION AND RELIABILITY IN PLANNING, ADJUSTING AND TESTING A EUROPEAN VLBI-CAMPAIGN; SURVEY OF ONGOING AND FUTURE MEASUREMENTS
F.J.J. Brouwer, Geodetic Computing Center - Delft (Netherlands)

17.00 CLOSING SESSION

IAG Symposium on Geodetic Networks and Computations
Munich, August 31 - September 5, 1981

GEODESY AND THE GLOBAL POSITIONING SYSTEM

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ABSTRACT. The 18 satellites at altitudes of 20 thousand kilometers proposed for the NAVSTAR Global Positioning System will provide an opportunity to determine the relative positions of sites hundreds of kilometers apart to accuracies on the order of centimeters after a few hours of observations. This presentation reviews recent efforts in the United States in the development of different geodetic receivers designed with the above goal in mind.

1. INTRODUCTION

This presentation, prepared at the request of the organizers of this symposium, is a review of the current (early summer, 1981) status of the NAVSTAR Global Positioning System (GPS). The 18 satellites at heights of some 20,000 kilometers proposed for the GPS will provide an opportunity to determine relative positions of sites up to hundreds of kilometers apart to centimeter-type accuracy after a few hours of observation, possibly less. The GPS and its navigational use is described in [Institute of Navigation, 1980]. Geodetic receivers to exploit the GPS signals are being developed mainly under the cognizance of a U.S. interagency coordinating group composed of representatives of the National Aeronautics and Space Administration (NASA), the Defense Mapping Agency (DMA), the Geological Survey, and the National Geodetic Survey (NGS). The most promising geodetic receiver developments and tests are being conducted with the support of this interagency group by the Jet Propulsion Laboratory (under NASA sponsorship) [MacDoran, 1981], and by the C.S. Draper Laboratory (CSDL) and the Massachusetts Institute of Technology (MIT) [Counselman, 1981], sponsored jointly by the other three agencies. DMA also continues to support activities at the Naval Surface Weapons Center (NSWC) with equipment by Stanford Telecommunications, Inc. [Anderle, 1980]. Receivers are also being developed by other commercial companies on their own. Most notable are those by the Canadian Marconi Company, Magnavox Advanced Products and Systems Co., and Texas Instruments, Inc. (see Table 3). Most of these developments are described on a continuing basis in the [CSTG Bulletins].

2. DESCRIPTION OF THE GPS

The GPS has been designed to provide for passive, all weather navigation from virtually any point on earth at any time. The GPS satellites will be operated by the U.S. Air Force for the U.S. Department of Defense. The GPS constellation of satellites (known as the "Space System Segment") was originally to have consisted of 24 satellites equally spaced in three orbit planes, with 12-hour periods. This would have provided for continuous all weather precise navigation, with four satellites always visible in good geometry (above five degrees altitude) for any point on earth. However, for budgetary reasons, the constellation has been cut to 18 satellites. These satellites will probably still be placed in the same orbits as originally planned, except that the six satellites in each orbit plane will not be equally spaced. Such a configuration will provide the best orbital geometry and visibility over the longest periods of time worldwide (although with losses of up to 40 minutes over an eight-hour period) [Jorgensen, 1980].

The GPS satellites themselves will employ precise atomic frequency standards to assure high oscillator stability and precise timing information. Each satellite will broadcast on two L-band frequencies, L_1 (1575.4 MHz) and L_2 (1227.6 MHz), with the two frequencies allowing the elimination of first-order ionospheric refraction by receivers. Three different codes will be modulated onto the L-band frequencies, these including a D code consisting of a satellite message (at the rate of 50 bits/second) and two pseudo-random noise (PRN) codes called the coarse/acquisition (C/A) and precision (P) codes. These latter two codes are respectively modulated onto the L-bands at frequencies of 1.022 MHz and 10.23 MHz, with the codes repeating every one millisecond for (C/A) and every 38 weeks for (P) (in practice, P will be reset every week). These codes serve three purposes: (a) to identify each satellite uniquely, (b) to provide for measurement of the signal travel time to the receiver by measuring the phase shift required to correlate the codes to receiver generated codes [Milliken and Zoller, 1980], and (c) to provide for restriction of the use of the system if desired, since the P code must be known a priori by the user to obtain the highest accuracy (except for certain types of receivers described later) [Stansell, 1980].

A normal GPS receiver would thereby have to complete the following operations to successfully track a satellite: (a) acquire and recognize the C/A code, (b) obtain the necessary satellite message information to obtain the P code epoch by decoding the D code from the C/A code, (c) acquire and recognize the P code.

The present status of the GPS is that six NAVSTAR satellites are presently in orbit (although one of them has a faulty clock). A seventh satellite is to be launched this summer, and the entire system is to be in operation by 1987. These satellites lie in two planes inclined at 63 degrees to the equator, allowing four satellite observations to be made (over three hours) from several locations, such as the U.S., a large portion of South America, Australia, the Near East, and above latitudes of ± 60° [Perreault, 1980]. Therefore, although limited somewhat in location and time, the system is now operational, so that testing or limited actual use of any GPS receivers is a possibility.

This description would not be complete without some mention of the ground facilities, which are known as the "Control Segment" of GPS. Four ground stations will continuously monitor all GPS satellites in view. The master control station will be located at Vandenberg Air Force Base, where all tracking data will be collected, with precise orbital information (predictions) then being made. This information will then be loaded into the satellite memory at least once per day as the broadcast message for the satellite. Further information on the Control Segment is available in [Russell and Schaibly, 1980] which also discusses the expected accuracy of the orbital predictions.

3. GPS OBSERVABLES

Three major methods of using the GPS satellites for precise positioning have been proposed, making use of pseudo-range, Doppler, and interferometric observations. Instruments either have been or are being constructed to observe the satellites using variations of these methods. Details of these proposals can be found in [Fell, 1980] along with extensive simulation studies and estimates of the accuracies of the various methods.

Pseudo-Range

This method of observation is the one with which GPS was initially designed to operate. It will be primarily used for navigation, although if used over an extended period of time would

provide geodetic accuracies. The observing procedure is as follows:

(a) The receiver correlates its generated PRN codes with those of the satellite (while also compensating for Doppler shift of the codes). The time shift (τ) necessary to make this correlation results from the range to the satellite and the receiver clock synchronization error ($\Delta\tau$). (Due to this synchronization error, this method is called pseudo-range and not range.)

(b) The value of τ must then be corrected for first-order ionospheric refraction, using either the τ values obtained from both L-band frequencies or a one-frequency model.

Therefore, subject to other minor error sources, the observation equation is

$$r = c\tau = |\vec{\rho}_s - \vec{\rho}| + c\,\Delta\tau = [(u_s - u)^2 + (v_s - v)^2 + (w_s - w)^2]^{\frac{1}{2}} + c\,\Delta\tau$$

where

c is the velocity of light

$\vec{\rho}_s$ $(u_s\ v_s\ w_s)^T$, earth-fixed satellite vector

$\vec{\rho}$ $(u\ v\ w)^T$, earth-fixed station vector

Since c, u_s, v_s, w_s are assumed to be known, there are four unknowns left, $\Delta\tau$, u, v, and w. An exact solution results if four satellites are observed simultaneously. This is the basis of the GPS navigation solution and of most of the GPS navigation receivers.

Simulation studies by Fell [1980] show that using this method in the dynamic (point positioning) mode, geocentric coordinates can be provided with an accuracy of approximately 50 to 80 cm after one day of observation, or 25 to 40 cm after five days of observation (see Table 1). Note

Table 1 Effect of Systematic and Random Error Sources on Dynamic Point Positioning Using One-Hour Satellite Tracking Intervals

ERROR SOURCE	APPROXIMATE COORDINATE ERROR (cm) RANGE 1 DAY	RANGE 5 DAYS	DOPPLER 1 DAY	DOPPLER 5 DAYS
TROPOSPHERIC REFRACTION	10	5	10	5
EPHEMERIS	50-80	25-40	60-150	30-70
RESIDUAL SATELLITE RUBIDIUM CLOCK ERROR	4	1	5	2
RECEIVER CESIUM CLOCK ERROR	5	2	7	3
RECEIVER WHITE NOISE (RANGE 1m, DOPPLER 3cm)	2	1	18	8

from [Fell, 1980, Table 6.2.1]

that this type of observation does not require observations to four satellites simultaneously, thereby simplifying the receiver and allowing continuous use anywhere in the world (since one satellite will always be well above the horizon). However, better oscillators (clocks) are assumed to have been used than those of the navigation receivers, and tropospheric refraction must be more carefully modeled. If two receivers are used to simultaneously observe the same satellites, higher accuracy may be obtained for the baseline. The simulations show that accuracies on the order of 3 cm for baseline lengths are possible, with tropospheric refraction and the receiver clocks introducing the most error (see Table 2).

Table 2 Effect of Systematic and Random Error Sources on Baseline Determination Using One-Hour Satellite Tracking Intervals

ERROR SOURCE	APPROXIMATE COMPONENT ERROR (cm) RANGE 1 DAY	RANGE 5 DAYS	DOPPLER 1 DAY	DOPPLER 5 DAYS	DOUBLE DIFFERENCED PHASE 6 HOURS
TROPOSPHERIC REFRACTION	6-8	2-3	4-8	2-3	2-4
EPHEMERIS	1-3	0.5-1.5	.5	.1	1-5
RESIDUAL SATELLITE RUBIDIUM CLOCK ERROR	.2	.1	.2	.1	-
RECEIVER CESUIM CLOCK ERROR	8	3	10	4	-
RECEIVER WHITE NOISE (RANGE 1m, DOPPLER 3cm, PHASE 3cm)	2-3	1-1.5	20-25	6-10	1-4

from [Fell, 1980, Table 6.3.1]

Doppler Observations

The observation method for Doppler is very similar to that of the pseudo-range. As explained for pseudo-ranges, a receiver must receive and correlate the PRN and D codes. Following this, the codes are removed, the resulting continuous wave carrier is compared with the local (receiver) oscillator, and the beat frequency is measured to obtain the Doppler count. This is the method presently used in the TRANSIT satellite system. Alternatively, the receiver must continuously shift its generated PRN codes to match the satellite's codes to correct for the Doppler effect. A measure of this shift also corresponds to the Doppler count N_{ijk}. With either method, the counts are then corrected and used in the standard range difference Doppler observation equation:

$$\Delta r_{ijk} = \frac{c}{f_o} [N_{ijk} - (f_o - f_s) (t_k - t_i)]$$

where

f_s is the reconstructed satellite frequency
f_o is the local generated frequency
t_k, t_i are the end and start times of the count N_{ijk} at station j

(The above equation neglects systematic error effects such as oscillator drift or tropospheric refraction.) According to Table 1, the accuracy of geocentric positions obtained by this method appears to be between 65 to 150 cm after one day of observation or 30 to 70 cm after five days of observation. This again assumes tracking of individual satellites for one hour at a time, with most of the uncertainty due to the satellite ephemeris. If a baseline is measured (see Table 2), accuracies of about 5 cm are also obtainable, assuming that receiver white noise contributes about 1 cm error. (This may be too low. The true value will depend on the actual instrument in use.) The limiting factor seems to be the receiver white noise.

Interferometric Observations

Basically three different types of interferometric observations have been proposed. Before explaining them individually, it is appropriate to note what they have in common. All of the interferometric methods would be used for baseline (actually baseline component) determination only. They assume that two stations will be observing the same satellite pass. This implies that the satellite(s) must be visible to both stations, so that for the GPS satellites, there is a limit of about 4000 km on the length of the baseline to be measured, and that the data at both stations must be correlated for a solution. One method makes use of measurements of the phases

of what are called the "reconstructed carrier" signals, with knowledge of the original modulation code being used in generating these signals. A second method makes use of knowledge of the general structure of the code, but not the code itself. A third method is similar to astronomical radio interferometry, but uses the GPS signals as the "noise" sources. No knowledge of the signal structure or the code is needed with this method. These methods are discussed below [NRC, 1981].

The *first method* makes use of nearly simultaneous measurements to two or more satellites from each ground station; the effects of station frequency standard instabilities can be almost eliminated in any of the methods. In the most favorable cases, the main accuracy limitation appears likely to result from the uncertainties in the radio wave propagation corrections due to water vapor content of the atmosphere. Water vapor radiometers probably will need to be used at both ends of the baselines to infer the integrated water vapor content along the lines of sight to the satellites to achieve centimeter-level accuracy, unless the baseline lengths are short. This is because the atmospheric water vapor content is likely to be quite variable in time and somewhat inhomogeneous spatially at many locations.

The basic principle of using the measured difference in phase for signals received at two sites to determine the component of the baseline in the direction of the source is well known from astronomical radio interferometry. Such measurements would be simplified if the signals transmitted by the GPS satellite were sinusoidal. Unfortunately, instead of being nearly monochromatic, the GPS signals have strongly suppressed carriers. The code modulation produces a spectrum spread over about 20 Mhz for each of the two frequency bands transmitted. However, signals equivalent to the carriers can be reconstructed in the ground receiver without much loss in the signal-to-noise ratios if the code used in the satellite is known. The basic idea is to generate a local oscillator signal that is 180° phase modulated in the same way as the signal from the satellite of interest, so that the beat between the two signals is nearly free of the modulation effects. The beat is used to produce a clean phase-locked output signal which will change its phase by one cycle each time the radio path length to the satellite changes by one wavelength. This is called a reconstructed carrier signal.

The reconstructed carrier phase method [Bossler et al., 1980] makes use of nearly simultaneous phase measurements for a particular satellite by receivers at both ends of a baseline. Only the phase difference between the signals received at the two ends is needed in the analysis, so that satellite clock instabilities cancel out. If the two receivers observe the phase differences between the signals from two satellites simultaneously (double-phase differencing) both satellite and ground clock errors cancel out. For example both receivers might switch simultaneously every second to a different satellite. In this case short switching time is needed to reduce the stability requirements on the receiver clocks.

Fell [1980] has performed simulation studies using the interferometric double phase differencing method also. Assuming observations on pairs of satellites from two stations over six hours, he determined that baseline errors were on the order of 2 to 4 cm for 100 km baselines (see Table 2). Other simulations show that the observation time may be shortened considerably [Bossler et al., 1980].

The *second method* is similar to the one just discussed in that signals equivalent to the reconstructed carrier signals are generated in the receivers. However, this is done without exact knowledge of the code being required.

Two versions of this method are being pursued currently. At the Jet Propulsion Laboratory, the SERIES system which is being built and tested uses directional antennas about 1.5 m in diameter to track individual GPS satellites (Fig. 1). Knowledge of the approximate switching rate for the code is employed to resolve ambiguities without the requirement for a long observing

Fig. 1 The SERIES Directional Antenna and Van
(*Photo courtesy of JPL.*)

time at each site, but no other information on the code is needed [MacDoran, 1981]. Another version of this method [Counselman, 1981] uses small, nearly omnidirectional antennas (Fig. 2) and a different data processing technique. Results so far indicate that reflection of the satellite signals from the ground or nearby structures is not a serious problem, even with the nearly omnidirectional antennas.

Fig. 2 The MITES Nearly Omnidirectional Antenna Placed on the Ground (*Photo courtesy of C.C. Counselman III*)

The *third method* is analogous to the one used with radio astronomical signals. The use of long-baseline radio interferometry with noise transmitted from a satellite was actually demonstrated some time ago. An adaptation of this method for accurate baseline determinations with the spread-spectrum GPS signals as the radio noise sources was the original SERIES proposed by MacDoran [1979, 1980]. Since the received flux density is about 10^{6} times larger than for extragalactic radio sources, the apparatus can be much less expensive and more compact than that needed for astronomical long-baseline interferometry.

The second method discussed above appears to be superior to the third one because it requires less data recording and processing to achieve a given signal-to-noise ratio. However, a comparison of the advantages of the first and second methods is difficult because of uncertainty concerning the future availability of the code to non-Department of Defense users. The Department of Defense is reported to be considering adopting a policy under which incomplete knowledge of the characteristics of the GPS signals by nonapproved users would limit the accuracy of absolute position determinations, but not of relative position determinations for which real time results are unnecessary. However, how this policy would be implemented is not known at present. It would be highly valuable if information on the future availability of the code and other related questions could be provided soon.

An additional interferometric approach which has been investigated jointly by MIT and Draper Laboratories involves placing some small supplemental transmitters on future GPS satellites [Counselman and Shapiro, 1979]. This would permit considerable simplification in GPS receivers for geodetic uses, which is highly desirable and would avoid ambiguity problems. However, it is not known what the chances are of adding the necessary equipment to the satellites. In the interim, demonstrations of both the reconstructed carrier interferometry method and the spread-spectrum interferometry method are being carried out to assess the accuracy likely to be achieved with the proposed future system.

Although there are still many uncertainties, the prospects seem good that all of the GPS interferometric methods being developed will achieve 3 cm accuracy for the three baseline components at a high confidence level. For very short baselines, about 100 m in length, Counselman [1981] has demonstrated 1 cm accuracy in each of the components. However, a much better knowledge of the range of errors associated with tropospheric water vapor in different regions is needed in order to clarify the prospects further. It seems clear that at least two of the GPS interferometric methods will be preferred over the use of astronomical long-baseline interferometry for baselines which are short enough so that the error contributions due to the GPS orbit uncertainties do not become substantial. Low GPS satellite orbit uncertainties are expected when accurate interferometric tracking data is available from a well-distributed set of fixed ground stations [MacDoran, 1979; Counselman and Shapiro, 1979].

Summary of Instruments

Table 3 lists geodetic GPS receivers, their stage of development, and different characteristics. This list is not meant to be complete, but merely gives some indication of the types of receivers presently being worked on.

It is obvious that with the current rate of development, geodetic receivers will be readily available by the time the GPS system is in full operation, with the interferometric instruments by then providing the highest baseline accuracies. However, the pseudo-range and Doppler instruments are already available and capable of providing station positions with accuracies similar to those obtainable using the TRANSIT system of satellites in conjunction with the by now "classical" Doppler integrator instruments.

Table 3 GPS Receivers (User Segment, Geodetic Use Only)

Name	Organization	Status	Size	Observable	Reference
CMA-782	Canadian Marconi Co.	Available commercially	Semi-portable (10" x 17" antenna)	Pseudo-range Doppler phase	Blaha 1980
STI-5010	Stanford Telecommunications Inc.	Available commercially	Van mounted	Pseudo-range Doppler	Perreault 1980
	Magnavox	Under development	Portable		Deem 1980
	Texas Instruments	Under development			Ward 1980
SERIES	Jet Propulsion Laboratory	Testing	Van mounted (1.5 m dish antenna)	Phase differencing Range	MacDoran 1981
MITES	Massachusetts Institute of Technology	Under development, antenna being tested	Portable	Phase differencing	Counselman 1981

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International Coordination of Space Techniques for Geodesy and Geodynamics

— CSTG —

IAG Commission VIII
International Association of Geodesy
International Union of Geodesy and Geophysics

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September 21, 1981

From: Ivan I. Mueller

Subject: Minutes of CSTG Meetings, Munich, September 2, 1981

The meeting of the Commission on International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG) was opened at 8:35 AM by the President, Ivan I. Mueller. Kenneth I. Daugherty was asked to act as secretary. The agenda for the meeting was distributed (Enclosure 1), items 1 through 7 being covered in this meeting. Sixteen people were present either as observers or members of CSTG (Encl. 2).

1. President's Report. Presented by Mueller. In response to questions regarding the MEDOC project, C. Boucher stated that data collection has been suspended on MEDOC until some improved methods for data analysis are available.

2. Subcommission Report. Boucher presented the report on the Subcommission on Standards. This report, together with the reports of the other subcommissions, is found in CSTG Bulletin No. 3.

3. Participation in Tokyo. Mueller reported that a half day (AM, May 14, 1982) had been set aside for CSTG at the IAG meeting in Tokyo in 1982. Present plan calls only for a business session, but there is some pressure to present some scientific papers. Robbins suggested a report on Project MERIT. Ch. Reigber suggested review papers on projects related to CSTG to cover scientific background and status. Mueller asked who would be in Tokyo, and the following responded: Robbins, Boucher, Giacaglia, Reigber and Prilepin. It was agreed that review papers of the above type would be solicited by the President.

4. Short Course in Manila. The Philippines proposed hosting a one-week short course on the applications of space techniques for geodesy and geodynamics to be held in Manila. It is proposed that if a special program were to be established, it should follow the IAG meeting in Tokyo in 1982, with from 10 to 12 experts going to Manila to offer technical lectures. CSTG, through COSPAR, has requested funding from ICSU for the travel. The President requested that everyone think about this and participate if possible. Let Mueller know in the next two months.

ACTION

C-2

5. Project ALGEDOP. Mueller reviewed a letter from A. Marussi proposing ALGEDOP (Alpine Geoid Doppler Project) (Encl. 3). The participants expressed support for this project provided that it can be soundly justified on a scientific basis. In this regard the main questions were the need for such a geoid and whether the accuracies achievable through Doppler are really superior to those obtainable through gravimetry.

6. WARC/SFCG Frequency Allocation. Reigber presented details of POPSAT. To support this project there is a need for an up/down link frequency allocation. The desired frequency is in the 2 gHz range. The POPSAT group would like CSTG to appeal to the appropriate authorities in support of setting aside the required frequency for their system. At this point, action on the item was suspended and was resumed during the afternoon session at 4:35. At that time Reigber briefly reviewed the international frequency allocation structure and procedures. A resolution was passed that the President write to the executive secretary of the International Space Frequency Coordination Group (SFCG) putting forth support for the frequency allocation for POPSAT (Encl. 4).

7. Other Business. As there was no other business the session was adjourned to be reconvened at 2:30 for a joint session with IAG Commissions X and XI.

Joint meeting of CSTG with IAG Commissions X and XI convened at 2:30, September 2, 1981. Mueller, R.O. Coker for Commission XI and R. Sigl for Commission X jointly chaired the meeting. See Encl. 1 for the agenda. Items 8 through 16 were covered during the meeting. Twenty-six persons attended (Encl. 5).

8. Introduction. Coker opened the meeting by reviewing the background of the Doppler project for Africa. He requested Mueller to continue the meeting and to cover the items on the agenda.

9. Resolutions of the Addis Ababa Symposium. Mueller gave the history of CSTG activities related to the Doppler project for Africa and outlined the sister nation concept which is being advocated by CSTG and Commission XI (Encl. 6).

10. Reports on Existing Projects or Proposals. Mueller called on the various representatives present to report on existing projects or proposals. The first of these was the Upper Volta project. P. Richardus reported on the Dutch project. It consists of 16 Doppler points as part of an overall survey program. The observations are being done with Marconi equipment.

L. Sjöberg reported on the Tanzania and Zambia projects proposed by Sweden (Encl. 7).

Daugherty reported on DMA projects and proposals. DMA has done work in Africa for a number of years and has established 60-80 points by Doppler point positioning. DMA currently has agreements with Egypt and Sudan which will involve additional Doppler points. DMA would like to establish bilateral

agreements with other African nations. DMA would furnish Doppler receivers and full teams (two persons) and would pay all expenses of their teams. Sister countries would be expected to supply local support and participate in the field program. All data would be reduced by DMA and results furnished to the sister nation for release. DMA is also proposing to serve as a computation center for the African Doppler project to reduce data using the precise ephemeris to establish Doppler point positions.

E. Reinhart reported on the Ivory Coast project (Encl 8).

S. Krynski described related activities by Poland (Encl. 9). Based on the Polish report Mueller asked the Polish representatives if they would prepare a plan for the Doppler survey of Africa to be presented at the Nairobi meeting in November and send it to CSTG and to Commissions X and XI by October 15. The Polish representatives agreed to do so.

ACTION

11. Results of the Surveys by Questionnaires. Mueller reviewed the results of the questionnaire which he had sent to countries who might be able to give support for the Doppler survey of Africa. A summary based on these questionnaires is provided in Encl. 10. This summary indicates that there is interest in at least 14 countries which together own more than 110 Doppler receivers of various types. Subsequent to the meeting Bulgaria and Brazil also forwarded their questionnaires which indicate interest in participation by a total of three Doppler receivers (one MX, JMR-1, CMA 761). A proposal for selection from these will be presented at the Nairobi meeting.

12. Development of Standards. Mueller introduced copies of the new Canadian manual on Doppler surveys and two DMA manuals on the same subject. He proposed that a committee of experts chaired by Boucher review the documents and make a recommendation by October 15 on standards of survey and documentation to be used in the African campaign. Boucher selected B.A. Sikilo, W. Schlueter and J. Critchley as members of his subgroup. The proposal for standards will be presented in Nairobi.

ACTION

13. Regional Centre for Services in Surveying and Mapping in Nairobi. Mueller stated that CSTG would encourage all computations to be done at two computing centers. The Regional Centre for Services in Surveying and Mapping in Nairobi has volunteered to be the African computing center. Those countries which have an interest in acting as a computing center should send a letter of interest by October 25 to CSTG and Commission XI describing their capability and experience in Doppler geodetic computations.

ACTION

14. Where Do We Go from Here? It is important that the plans and as many arrangements as possible be ready before the Nairobi meeting. Interested parties should go to Nairobi prepared to discuss details of the African Doppler program. It was agreed that the President should again contact all African countries, inform them about the outcome of this meeting, and encourage them to participate at the Nairobi meeting.

15. The Meeting in Nairobi in November, 1981. At the meeting in Nairobi it is the desire of the CSTG and Commission XI members present that our business be conducted during the first week, if possible. Coker agreed to arrange for such

meetings on November 10 and 13. In the meantime, J.D. Obel, Secretary of the Nairobi conference indicated that the CSTG meetings would be scheduled November 13, 16 or 17. CSTG is now planning to meet on the 13th and 16th. As described above, during this meeting the following will be presented:

-- plan of Doppler stations
-- draft of specifications for the survey
-- designation of computing centers
-- a draft statement which would need to be part of any bilateral agreement without which the survey will not qualify as part of this project
-- proposal for the designation of sister countries
-- dates for the campaign (see below)

16. Other Business. There being no other business the joint meetings were adjourned. At a later informal meeting, the suggestion was made that the Doppler survey should be conducted during a specified one- to three-month period during which time precise ephemerides of all NNSS satellites would be available, sometime during 1982/83. Daugherty was requested to report at the Nairobi meeting on such time periods.

Note: The enclosures, omitted here, may be obtained on request from the President of CSTG.